Hypnotic Suggestions: Their Nature and Applicability in Studying Executive Functions

Dissertation

zur Erlangung des akademischen Grades Doktor rerum naturalium (Dr. rer. nat.)
im Fach Psychologie

Eingereicht an der

Lebenswissenschaftlichen Fakultät
der Humboldt-Universität zu Berlin

von

M.S. Anoushiravan Zahedi

Präsidentin der Humboldt-Universität zu Berlin
Prof. Dr. – Ing. Dr. Sabine Kunst

Dekan der Lebenswissenschaftlichen Fakultät
Prof. Dr. Christian Ulrich

Gutachter/in: 1. Prof. Dr. Sebastian Markett

2. Prof. a. D. Dr. Werner Sommer

3. Prof. Dr. Christine Stelzel

Tag der mündlichen Prüfung: 31.05.2021

Table of Contents

Acknowledgments

I remember the first time that I met Prof. Dr. Werner Sommer vividly. At the time, I was in the middle of designing the study, which later became the foundation of my master's thesis. Unbeknown to me, the design of the study had a simple but fundamental issue. Even though I theoretically knew preemptive measures that could be taken against this issue, but I did not grasp the importance of implementing these measures when designing real experiments. Thankfully, Prof. Sommer pointed out that issue to me, and we preemptively solved it, which later helped us publish the work in a well-known journal. This incident was, however, only the beginning of constant support and guidance that I received from him and Prof. Dr. Birgit Stürmer, who later become my Ph.D. supervisor and co-supervisor, respectively. I shall thank both of them wholeheartedly since, without them, this path would have been much more ominous and difficult. The constant support that I received from my supervisor, however, does not decolor the help of so many other interns, bachelor and master students who rigorously supported this project through helping with EEG recordings, participant recruitments, administrating experimental sessions, and so forth. To name only a few of them, I thank Dilara Dilekçe, Sophie Dunn, Lauren Paterson, Lukas Wiegmann, Katja Zellner, Rowena Piers, Eloise Funnel. I apologize to many other kind individuals who helped me through this path, but I forgot to mention their names here.

I thanked so many people, but yet need to thank two persons without whom this journey was impossible to be undertaken. My mother, Shahdokht Haghdoust, and my kind spouse, Forough Hassanibesheli, did not only help me through this path but sometimes gave me the motivation to continue this adventure. Therefore, it is only appropriate for me to, besides thanking them unreservedly, dedicate this work to them.

Original Research Articles

1. Zahedi, A., & Sommer, W. (submitted). How hypnotic suggestions work – critical review of prominent theories and a novel synthesis. doi:10.31234/osf.io/mp9bs

2. Zahedi, A., & Sommer, W. (submitted). Is there a G-factor in Hypnotic Suggestibility? Confirmatory Factor Analysis of the Harvard Group Scale of Hypnotic Suggestibility.

3. Zahedi, A., Łuczak, A., & Sommer, W. (2020). Modification of food preferences by posthypnotic suggestions: An event-related brain potential study. *Appetite*, 151, 104713. doi:10.1016/j.appet.2020.104713

4. Zahedi, A., Stürmer, B., & Sommer, W. (2020). Can posthypnotic suggestions boost updating in working memory? Behavioral and ERP evidence. *Neuropsychologia,* 148, 107632. doi:10.1016/j.neuropsychologia.2020.107632

5. Zahedi, A., Abdel Rahman, R., Stürmer, B., & Sommer, W. (2019). Common and specific loci of Stroop effects in vocal and manual tasks, revealed by event-related brain potentials and posthypnotic suggestions. *Journal of Experimental Psychology: General*, 148(9), 1575-1594. doi:10.1037/xge0000574

Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt,

1. dass ich die vorliegende Arbeit selbstständig und ohne unerlaubte Hilfe verfasst habe,

2. dass ich mich nicht anderwärts um einen Doktorgrad beworben habe und noch keinen Doktorgrad der Psychologie besitze,

3. dass mir die zugrunde liegende Promotionsordnung der MNF II vom 5. März 2015., veröffentlicht im Amtlichen Mitteilungsblatt der HUB Nr. 12/2015 bekannt ist.

Berlin, den 20. 01. 2021

Anoushiravan Zahedi

Abstract

Executive functions are a group of top-down processes used in novel situations to develop new trigger-response contingencies or adapt existing responses to the task at hand. Even though several taxonomies of executive functions suggest that there are three (semi-)distinguishable functions, several important questions remain unanswered. Three critical examples are (a) Unity versus diversity: are these functions entirely separated top-down processes, or do they rely on a common underlying neurocognitive system? (b) Vocal and manual Stroop tasks: what do different versions of the Stroop task, one of the most common tasks used for tapping into the inhibition function, measure? (c) Resolving or suppressing: does inhibition always need to be effortful, or is there a subcomponent of inhibition that can be implemented effortlessly? To address these questions, I investigated neurocognitive correlates of executive functions and their enhancements by means of posthypnotic suggestions and event-related brain potentials (ERP). However, before one can use suggestions for investigating top-down processes, such as executive functions, it must be elucidated how they affect performance in cognitive tasks. Although task-relevant posthypnotic suggestions are used repeatedly for improving performance in inhibition tasks, it is unclear whether these enhancements are mediated by changes in bottom-up or top-down processes. By using an updating task, I showed that the effects of task-relevant posthypnotic suggestions on cognitive tasks can indeed be attributed to alterations in top-down processes and enhanced deployment of executive functions. Based on this finding, a new theory of hypnosis, the simulation-adaption theory (SATH), was proposed and empirically tested by modeling hypnotic-suggestibility scores with confirmatory factor analysis and structural equation modeling. SATH suggests that three top-down cognitive processes are employed by willing and cooperative participants for responding to suggestions, namely, cognitive-simulation, sensory-adaptation, and mental practice. After elucidating that the driving mechanism of task-relevant posthypnotic suggestions is mentally practicing a novel strategy, posthypnotic suggestions were used for addressing the above-mentioned questions regarding executive functions. Summarizing the findings (a) the psychometric and ERP results from several studies were employed to investigate updating and subcomponents of inhibition, and their enhancements by means of posthypnotic suggestions. The findings indicated that inhibition and updating rely on both function-specific and shared neurocognitive processes. In other words, there is both unity and diversity of executive functions. (b) Even though both the vocal and manual versions of the Stroop task are tapping into the inhibition function, the vocal version is more taxing, as it has at least an extra response-production-related locus of interference, which is not affected by posthypnotic suggestions and is absent in the manual version. (c) Using posthypnotic suggestions for increasing and – by contrast – diminishing preferences for low- versus high-calorie food items, I investigated the implementation of resolve. The results showed that, similar to suppression, resolve is effortful to implement, as indicated by increased P300 amplitudes. Together, this project shows how employing task-relevant suggestions along with neuroimaging techniques can provide a novel approach for investigating long-lasting questions about executive functions and top-down processes.

Keywords: Hypnosis, Executive Functions, Unity versus Diversity, suggestions, mental practice, manual Stroop task, vocal Stroop task, Resolve, Suppression, working memory, updating.

Zusammenfassung

Exekutive Funktionen sind eine Gruppe von Top-Down-Prozessen, die in neuartigen Situationen eingesetzt werden, um neue Trigger-Response-Assoziationen herzustellen oder vorhandene Handlungsoptionen an neue Situationen anzupassen. Obwohl mehrere Taxonomien drei (semi-)unterscheidbare Typen von Exekutivfunktionen vorschlagen, bleiben wichtige Fragen offen. Beispiele dafür sind (a) Einheit versus Vielfalt: Sind Exekutivfunktionen vollständig trennbar oder beruhen sie auf einem gemeinsamen neurokognitiven System? (b) Vokale und manuelle Stroop-Aufgaben: Was messen verschiedene Versionen der Stroop-Aufgabe, einer der meist-verwendeten Aufgaben zur Prüfung der Inhibitionsfunktion? (c) Auflösung oder Unterdrückung: Muss Inhibition immer Ressourcen-fordernd sein, oder gibt es eine Form der Inhibition, die mühelos implementiert werden kann? Zur Beantwortung dieser Fragen, habe ich neurokognitive Korrelate von Exekutivfunktionen und ihrer Verbesserung mithilfe posthypnotischer Suggestionen und Ereigniskorrelierter Hirnpotentiale (EKP) untersucht. Bevor man jedoch Suggestionen zur Untersuchung von Top-Down-Prozessen, wie z.B. Exekutivfunktionen einsetzen kann, muss geklärt werden, wie sie sich auf die Leistung in kognitiven Aufgaben auswirken. Obwohl aufgaben-bezogene posthypnotische Suggestionen schon oft zur Leistungs-Steigerung in Inhibitionsaufgaben verwendet wurden, ist unklar, ob diese Verbesserungen auf Änderungen in Bottom-Up- oder Top-Down-Prozessen beruhen. Durch die Verwendung einer Arbeitsgedächtnis-Aktualisierungsaufgabe konnte ich zeigen, dass sich Aufgaben-bezogene posthypnotische Suggestionen in der Tat auf Top-Down-Prozesse und eine verbesserte Bereitstellung von Exekutivfunktionen auswirken. Basierend auf diesem Befund wurde eine neue Hypnosetheorie, die Simulations-Adaptionstheorie (SATH), vorgeschlagen und empirisch geprüft, indem hypnotische Suggestibilitäts-Daten mit Konfirmatorischen

Faktorenanalysen und Strukturgleichungen modelliert wurden. SATH postuliert, dass willige und kooperative Probanden drei Top-Down Prozesse einsetzen, um auf Suggestionen zu reagieren, nämlich kognitive Simulation, sensorische Anpassung und mentale Übung. Nachdem mentale Übung als bedeutsamer Mechanismus für aufgaben-bezogenen posthypnotische Suggestionen nachgewiesen wurde, habe ich posthypnotische Suggestionen eingesetzt, um die oben aufgeführten Fragen zu Exekutivfunktionen zu klären. Zusammenfassend ergaben sich folgende Antworten: (a) Psychometrische und EKP-Daten aus den Studien zur Gedächtnisaktualisierung und Inhibition sowie deren Verbesserung anhand posthypnotischer Suggestionen zeigten sowohl funktionsspezifische als auch gemeinsame neurokognitive Prozesse der Inhibition und Aktualisierung. Mit anderen Worten, es gibt sowohl einheitliche als auch spezifische Komponenten von Exekutivfunktionen. (b) Obwohl sowohl die vokale als auch die manuelle Version der Stroop-Aufgabe Inhibitionsfunktionen erfordern, ist die vokale Version Ressourcen-fordernder, da sie mindestens einen zusätzlichen Lokus der Interferenz im Antwort-Produktionsprozess aufweist, der nicht mit posthypnotischen Suggestionen beeinflussbar ist und der in der manuellen Version fehlt. (c) Unter Verwendung posthypnotischer Vorschläge zur Erhöhung und - im Gegensatz dazu - Verringerung der Präferenzen für kalorienarme und kalorienreiche Lebensmittel untersuchte ich die Auflösung von Konflikten. Die EKP-Ergebnisse zeigten, dass auch Konflikt-Auflösung, ähnlich wie Inhibition, Ressourcen konsumiert. Insgesamt zeigt dieses Projekt, dass die Verwendung Aufgaben-bezogener Suggestionen in Kombination mit Neuroimaging-Techniken einen fruchtbaren Ansatz für die Untersuchung ungeklärter Fragen über Exekutivfunktionen und Top-Down-Prozesse darstellt.

Schlüsselwörter: Hypnose, Exekutive Funktionen, Einheitlichkkeit und Spezifität, Suggestions, Mentales Üben, Stroop-Aufgabe, Konfliktlösung, Inhibition, Arbeitsgedächtnis, Aktualisierung.

To Finish is our Goal

To Thrive is our Hope

To Transcend is our Dream

Synopsis of Dissertation

1. Introduction

As Heraclitus put it, “the only constant in life is change.” Even though natural selection offers a unique way for species to adapt themselves to long-lasting environmental changes, it cannot be of any help for individuals facing rapid changes in their surroundings (Campbell et al., 2018). Individuals of most species are confined to stimulus-driven actions. However, bottom-up stimulus-driven actions are not sufficient for handling a novel situation, for which there is no preexisting stimulus-response contingency. Intriguingly, evolution had bestowed a set of cognitive capabilities to primates in general and particularly humans for flexibly adapting their actions to novel situations by using their greatly enlarged prefrontal cortex (Baddeley & Hitch, 1974; Gazzaniga, 2000; Goldman-Rakic, 1991; Goldman-Rakic, 1995). A group of top-down processes called executive functions, which strongly rely on the prefrontal cortex (for review, see Alvarez & Emory, 2006; Rottschy et al., 2012; Yuan & Raz, 2014), provide the basis of this cognitive adaptability (Baddeley, 1996, 2003; Baddeley & Hitch, 1974).

1.1. Executive Functions

For the first time suggested by Baddeley and Hitch (1974), the term “executive function” was used to describe cognitive functions attributed to the central executive unit, which is a module in working memory (Baddeley, 1996, 2003). Working memory, in contrast to short-term memory (Atkinson & Shiffrin, 1968), is not a mere inactive depository between sensory and long-term memory but an active component that provides an interface for communication between perceptions, actions, and cognitions. Even though there is a consensus that for understanding human cognition, it is necessary to assume a group of “executive” functions (Baddeley, 1996, 2003; Norman & Shallice, 1986), defining these functions is a more contentious matter (Baddeley, 2003; Miyake et al., 2000). Many approaches, such as structural equation modeling (e.g., Karr et al., 2018; Miyake et al., 2000), neuroimaging (e.g., Collette et al., 2005; Miyake & Friedman, 2012; Smolker, Friedman, Hewitt, & Banich, 2018), and metanalysis (e.g., Niendam et al., 2012; Rottschy et al., 2012; Wager & Smith, 2003), have been used to offer a parsimonious number of executive functions. Based on these investigations, there is a tentative consensus that one needs to assume three (semi-)distinguishable executive functions to adequately interpret existing observations in the literature (for review, see Diamond, 2013; Miyake et al., 2000). These functions are (1) updating: storing, retrieving, and substituting information in working memory buffers. (2) Inhibition: suppressing prepotent but task-inappropriate actions. And (3) shifting: redistributing attentional resources between sub-tasks (Diamond, 2013; Miyake et al., 2000). However, several important questions regarding the structure and nature of these functions are not addressed yet. In the following, three critical questions are going to be presented in more detail.

1.1.1. Does Unity Describe Executive Functions better or Diversity?

The first question is whether executive functions share a common neurocognitive structure (i.e., the unity proposition), or they are entirely separated (i.e., the diversity proposition) (Collette et al., 2005; Miyake & Friedman, 2012; Miyake et al., 2000; Niendam et al., 2012). Both psychometric and neuroimaging approaches are employed for addressing the question of unity versus diversity of executive functions. For instance, by using confirmatory factor analysis and structural equation modeling, Miyake et al. (2000) had investigated psychometric data obtained from 9 different cognitive tasks. Although their results indicated that a model with three latent factors can explain their data better compared to one- or two-factor models, latent factors in the three-factor model were strongly correlated with each other (i.e., $r_{shifting-updating} = .56$; $r_{inhibition-updating} = .63$; $r_{shifting-inhibition} = .42$). Therefore, the findings of Miyake et al.

(2000) can corroborate both accounts. Regarding the diversity proposition, the one-factor model was significantly worse than the three-factor model. Therefore, assuming diversity of executive functions might be necessary for explaining empirical evidence. Simultaneously, these results can be interpreted in favor of the unity proposition, as latent factors in the three-factor model were strongly correlated.

When considering executive functions at the cognitive level, it should be noticed that not all studies converge on the results of Miyake et al. (2000). For instance, in a systematic review and re-analysis of existing confirmatory factor analyses of executive functions, Karr et al. (2018) noted that the results of many studies (especially those focusing on child/adolescent samples) indicate that a model with one-factor (i.e., the unidimensional model) can explain their data better than a three-factor model. These results can further complicate the question of unity versus diversity of executive functions.

At the neural level, the existing observations are inconclusive, as well. For instance, inspired by the work of Miyake et al. (2000), Collette et al. (2005) recorded positron emission tomography (PET) during performing several cognitive tasks, measuring updating, shifting, and inhibition, to compare brain areas activated by each executive function. Their results indicated that there are several foci of activation common to all tasks, such as the right intraparietal sulcus, the left superior parietal gyrus, and the left lateral prefrontal cortex. However, their results also indicated that there are function-specific foci of activation. For instance, performing inhibition tasks but not updating or shifting tasks is correlated with activation of the left middle frontal gyrus and the (bilateral) inferior frontal cortex. The results of Collette et al. (2005) are in line with the conclusions of several metanalyses (e.g., Niendam et al., 2012; Rottschy et al., 2012; Wager & Smith, 2003) that have shown there are both common and function-specific foci of activation.

Therefore, the results of neuroimaging studies can also corroborate both the unity and diversity propositions. Concerning, the existence of function-specific foci of activation might indicate that different executive functions rely on distinguishable neural systems. However, common foci of activation might be interpreted as an indicator that a shared *attentional system* exists, required for every task, regardless of the function that it measures.

Why cannot existing neuroimaging results firmly corroborate one of these two accounts? A general criticism regarding the above-mentioned neuroimaging studies is related to the low temporal resolution of fMRI, PET, and similar methods with a high spatial resolution (Amaro & Barker, 2006). In a typical study using these techniques, neuroimaging data are recorded while subjects participate in a cognitive task, and then, averaged brain activity for each condition is calculated. Consequently, the foci of activation during task completion can be related to the perception of stimuli, processing, or response production (Amaro & Barker, 2006; Constable, 2006); however, only processing is related to executive functions. This issue, hence, might be the underlying reason for the inconclusiveness of neuroimaging results with regard to the question of unity versus diversity. A method that has been used for circumventing this issue is comparing data collected from multiple tasks measuring a specific function (e.g., Collette et al., 2005) or conducting metanalyses of studies using different tasks for measuring a given function (e.g., Rottschy et al., 2012; Wager & Smith, 2003). In this way, those foci of activation shared between several tasks that measure a given function are considered to be related to the targeted function. However, the low temporal resolution still does not allow a firm conclusion to be made about the functional role of a given focus of activation (Amaro & Barker, 2006; Constable, 2006).

A solution for avoiding issues related to the low temporal resolution of the above-mentioned neuroimaging techniques is using EEG and event-related brain potentials (ERP).

Innumerable studies had employed ERPs for investigating executive functions (e.g., Badzakova-Trajkov, Barnett, Waldie, & Kirk, 2009; Brouwer et al., 2012; Dong, Reder, Yao, Liu, & Chen, 2015; Evans, Selinger, & Pollak, 2011; Liotti, Woldorff, Perez, & Mayberg, 2000; Nakao, Kodabashi, Yarita, Fujimoto, & Tamura, 2012; Scharinger, Soutschek, Schubert, & Gerjets, 2017; Watter, Geffen, & Geffen, 2001). Notably, empirical evidence shows that the increase in the load of executive function tasks is correlated with the increase of P300 amplitude, a positive deflection around 300-500 ms after stimulus onset (for review, see Fonken, Kam, & Knight, 2020; Polich, 2007). However, one should notice that the definition of task load can vastly differ from one cognitive task to the other. Let us consider the Stroop and the N-back tasks, measuring inhibition and updating, respectively. In the Stroop task, color words, written in different ink colors, are consecutively presented to participants as they are instructed to identify the ink color of a given word while ignoring the meaning (MacLeod, 1991; Stroop, 1935; Zahedi, Stuermer, Hatami, Rostami, & Sommer, 2017). Since reading is a prepotent, habitual response, it cannot be easily suppressed despite being irrelevant in the Stroop task. Hence, commonly in the Stroop task, three task loads, namely incongruent, congruent, and neutral, are defined based on the existence of interference, facilitation, or no interaction, between an irrelevant source of information (i.e., word meanings) and a relevant one (i.e., ink colors), respectively. In the N-back task, however, stimuli, such as written letters, are consecutively presented to participants as they are instructed to determine whether the current stimulus and the one presented *N* steps back are similar. Therefore, different task loads in the N-back task are related to the number of items that should be actively maintained in working memory. Consequently, the increase in P300 amplitude, corresponding to the increased task load in the Stroop versus the N-back tasks, can be neural markers of vastly different cognitive processes, which might be irrelevant to executive functions, per se.

In order to compensate for the different definitions of task load across executive function tasks, one can suggest using interventions that aim to enhance executive functions and compare the neural correlations of these enhancements. In this way, regardless of the definition of task load, changes in the deployment of a function can be compared across cognitive tasks measuring different executive functions. One such intervention is using posthypnotic suggestions for enhancing performance in cognitive tasks (e.g., Augustinova & Ferrand, 2012; Iani, Ricci, Baroni, & Rubichi, 2009; Iani, Ricci, Gherri, & Rubichi, 2006; Lindelov, Overgaard, & Overgaard, 2017; Palfi, Parris, McLatchie, Kekecs, & Dienes, 2020; Parris, Hasshim, & Dienes, 2021; Raz, Fan, & Posner, 2005; Raz, Kirsch, Pollard, & Nitkin-Kaner, 2006; Raz et al., 2003).

In the current project, therefore, I used posthypnotic suggestions for enhancing performance in several tasks, measuring different executive functions, and compared neurocognitive correlates of enhancements in these tasks for addressing the question of unity versus diversity of executive functions.

1.1.2. What Do Manual and Vocal Versions of The Stroop Task Measure?

The Stroop and Stroop-like tasks, such as the emotional Stroop task (Williams, Mathews, & MacLeod, 1996) and the picture-word interference paradigm (Shitova, Roelofs, Schriefers, Bastiaansen, & Schoffelen, 2016; Starreveld & La Heij, 2017; van Maanen, van Rijn, & Borst, 2009) are among the most common tasks used for tapping into the inhibition function (MacLeod, 1991). In the Stroop and Stroop-like tasks, two kinds of information superimposed on each other are presented simultaneously, one task-relevant and the other task-irrelevant, which are processed effortfully and automatically, respectively. For producing the correct response, task-irrelevant information (e.g., the word meanings in the Stroop task) must be suppressed in favor of the task-relevant one. Even though taxing, in most cases, participants can successfully deploy their cognitive control processes for responding correctly to the Stroop task (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Cohen, Dunbar, & McClelland, 1990; MacLeod, 1991).

The initial version of the Stroop task (Stroop, 1935) and those used nowadays in neurocognitive studies have several important differences. In the initial version, several color-words written in different colors were printed on a card in multiple columns and rows, side by side, and participants needed to name the ink colors one by one while ignoring the word meanings (Stroop, 1935). In the newer versions, however, firstly, words are presented consecutively (i.e., single-trial), and secondly, participants need to press corresponding buttons to the ink colors (i.e., the manual version) instead of naming them (i.e., the vocal version) (MacLeod, 1991). Each one of these differences might change the required cognitive control processes altogether. For instance, in contrast to the card version, the single-trail version does not require selective attention, as the contextual interference is eliminated (Kindt, Bierman, & Brosschot, 1996).

The second change, that is, using the manual rather than the vocal output modality, was first integrated into the Stroop task to make it appropriate for being used in EEG and ERP studies. In other words, since naming the ink colors would have caused substantial articulation artifacts, researchers developed the manual version, so responses can be produced without moving facial muscles (Liotti et al., 2000; Redding & Gerjets, 1977; Sharma & McKenna, 1998). However, it is a matter of debate whether the vocal and manual versions are measuring similar (Dhooge & Hartsuiker, 2010, 2011; Geng, Schnur, & Janssen, 2013) or different cognitive functions (Liotti et al., 2000; Redding & Gerjets, 1977; Sharma & McKenna, 1998). Recently, there is a resurrected interest in investigating what forms of interference these two versions of the Stroop task are measuring (Augustinova, Parris, & Ferrand, 2019; Banich, 2019; Parris et al., 2019).

In the current project, I employed two novel techniques for investigating the commonalities and differences between these two task versions. First, as mentioned above, the EEG and ERP data from the vocal version cannot be analyzed due to articulation artifacts. Here, however, the problem of articulation artifacts was solved by applying the residue iteration decomposition method (RIDE; Ouyang et al., 2016) that can separate the brain-derived ERPs from overlapping articulations artifacts. Second, there are many studies showing that posthypnotic suggestions can reduce interference in the manual version of the Stroop task (Augustinova & Ferrand, 2012; Raz et al., 2005; Raz et al., 2003; Zahedi et al., 2017). However, to the best of my knowledge, no previous study used posthypnotic suggestions for reducing Stroop effects in the vocal version. Therefore, in the current project, I used posthypnotic suggestions to affect both the manual and vocal task versions to compare the loci of interference in these two tasks. Using these two techniques, that is, task-relevant posthypnotic suggestions and ERPs, I could functionally localize the Stroop effects in these two versions.

1.1.3. Does Inhibition Always Need to be Effortful?

Many researchers in the field of cognitive control and executive functions suggested that two subcomponents of the inhibition function should be separated, that is, suppression and resolve (for review, see Ainslie, 2020; Diamond, 2013). Commonly used inhibition tasks, such as the Stroop task (MacLeod, 1991), are focused on the short-term effort to suppress a prepotent, habitual, irrelevant trigger-response contingency and substitute it with an appropriate one. This form of inhibition, called suppression, requires an immediate mental effort that results in mental fatigue (Hockey, 2011; Shenhav et al., 2017). Notably, mental fatigue must not be confused with the depletion of resources, such as being out of fuel (Hockey, 2011). Instead, mental fatigue can be considered as the consequence of the aversiveness of using cognitive control instead of relying on automatic processes (Botvinick & Braver, 2015; Shenhav et al., 2017).

However, in quotidian events, another aspect of inhibition is also of great relevance, that is, forming motivational contingencies for overriding temptations. This form of inhibition can be designated as resolve (Ainslie, 2020). Let us examine situations that delaying immediate smaller gratification can cause a later, more significant outcome. In these situations, conflict arises as there are two possibilities, one results in a smaller-faster, and the other, in a bigger-slower reward (Mischel, Shoda, & Rodriguez, 1989). For handling these conflicts, one can stay focused on the desired behavior (choosing the bigger-slower reward) and suppress distracting information (Diamond, 2013; Mischel et al., 1989). Alternatively, the desired action can be exerted by changing one's preferences to make the bigger-slower option more appealing and/or the smaller-faster one less incentivizing. This latter form of cognitive control is related to the resolve function (Ainslie, 2020; Diamond, 2013). A frequently-encountered situation that demand delayed gratification is when one wants to decide between delicious high- versus insipid low-calorie food items, as the former is appealing but has negative long-term consequences and the latter is less tasty but healthier and more environmentally-sustainable (Clark, Springmann, Hill, & Tilman, 2019). For achieving the desired action of choosing the low-calorie food, one can either (I) suppress the temptation to pick delicious high-calorie food and stay focus on the low-calorie food, or (II) form a motivational contingency regarding the low-calorie option, such as connecting it to a more critical issue like self-worth.

An important question about resolve is whether its implementation is effortful? One can postulate that resolve immediately results in dissolving the conflict at hand and, therefore, can be implemented effortlessly (Ainslie, 2020). On the other hand, it can be proposed that resolve, at the time of implementation, is as effortful as suppression, since during resolve one needs to halt a habitual response and employ cognitive control processes for developing a new trigger-response (motivational) contingency, which, as discussed above, is effortful (Botvinick & Braver, 2015; Diamond, 2013; Shenhav et al., 2017). However, there is an intimidating obstacle in the way of addressing this question; that is, resolve does not lend itself easily to be manipulated or measured by commonly available experimental paradigms (Ainslie, 2020). In other words, for manipulating or measuring resolve, it is necessary to affect participants' intrinsic preferences and not extrinsic reward and punishment regimes. For instance, if the bigger-slower option will be incentivized by increasing its appeal, then the conflict is solved externally by changing the balance between the smaller-faster and bigger-slower options, rather than by manipulating participants' preferences.

However, there are many examples of clinical (for review see Hammond, 1990; Hammond, 1998; Kirsch, 1996; Milburn, 2010; Milling, Gover, & Moriarty, 2018) and experimental (Ludwig et al., 2014) applications of hypnotic and posthypnotic suggestions that target participants' preferences, making them an appropriate experimental manipulation for addressing the effortfulness of resolve. For instance, Ludwig et al. (2014) used posthypnotic suggestions to induce disgust toward pictures containing different food categories when they were superimposed on a background with a specific color. Even though their posthypnotic suggestion was targeting the background color and not the food stimuli themselves, the changes in perception were correlated with decreased activity in the ventromedial prefrontal cortex (vmPFC), which indicates that posthypnotic suggestion possibly caused participants to devalue objects suggested to be disgusting.

Therefore, in the current project, I used posthypnotic suggestions for affecting (food) preferences to manipulate resolve. Then, by measuring neurocognitive correlates of changes in preferences in a Go-NoGo task, measuring inhibition (Enriquez-Geppert, Konrad, Pantev, &

Huster, 2010; Liu, Xiao, & Shi, 2017), and comparing them with effects of increased deployment of suppression in the Stroop task, the effortfulness of resolve was investigated.

1.2. Hypnosis

For responding to the above-posed questions, I argued that using posthypnotic suggestions can be of great importance. However, before using suggestions for studying these questions, one fundamental issue should be addressed: How do posthypnotic suggestions affect performance in cognitive tasks? For instance, if the effects of posthypnotic suggestions are mediated by changes in bottom-up processes, they can be of no help in investigating top-down processes, such as executive functions. In the following, I will, firstly, present a procedural description of hypnosis and then try to demonstrate that previous theories of hypnosis have severe problems in elucidating the driving mechanisms of task-relevant posthypnotic suggestions.

Hypnosis commonly consists of three semi-distinguishable stages (Hammond, 1998; Kihlstrom, 2008), namely, induction, deepening, and termination. All three stages are induced through presenting suitable suggestions to a given participant by another person, designated the hypnotist (Kihlstrom, 1985; Lynn, Green, et al., 2015; Lynn, Laurence, & Kirsch, 2015). The term "suggestion" highlights that participants are going to experience intentional responses that can be distinguished from "instruction" or "command" that allude to nonvoluntary acts (Kirsch, 1999).

For inducing hypnosis, many different suggestions can be used (Hammond, 1998), all of which aim to (1) establish some basic expectancies about the procedure (Braffman & Kirsch, 1999) and (2) attract participants' attention and cause absorption in the presented suggestions and in their thoughts and feelings (Brown, Antonova, Langley, & Oakley, 2001). However, several studies have shown that hypnotic induction might have no effect on participants' responsiveness to suggestions (Mazzoni et al., 2009; McGeown et al., 2012).

Hypnotic induction might be followed by deepening, in which case, more suggestions aiming to induce relaxation will be presented to participants. Alternatively, suggestions following induction may be directed toward a targeted change in overt behavior, perception, or cognition, in which case, they are called hypnotic and posthypnotic suggestions. Posthypnotic suggestions, in contrast to hypnotic suggestions, will become effective only after the termination of hypnosis. Usually, for activating and deactivating posthypnotic suggestions after the termination of hypnosis, a cue, mentioned in the suggestions, will be presented, such as the sound of a specific ring. This process is called anchoring.

Finally, a suggestion at the end of hypnosis will cue the hypnotic procedure's termination, aiming to re-establish the previous expectancies about the external world and the effects of one's own behavior and actions (Hammond, 1998; Shor & Orne, 1962).

1.2.1. Effects of Posthypnotic Suggestions on Executive Function Tasks

It is well-established that posthypnotic suggestion can enhance performance in various cognitive tasks, such as the Stroop (e.g., Parris, Dienes, & Hodgson, 2012; Raz et al., 2005; Raz et al., 2006; Zahedi et al., 2017), Eriksen (Iani et al., 2006), and Simon tasks (Iani et al., 2009). Noticeably, most published experimental studies applying posthypnotic suggestions have focused on tasks capitalizing on the inhibition function (for review, see Lifshitz, Aubert Bonn, Fischer, Kashem, & Raz, 2013). Such tasks require refraining from a habitual, prepotent response in favor of a novel trigger-response contingency. The immediate implementation of the required response is difficult to achieve for most participants. For instance, in the Stroop task, attending to ink colors while ignoring word meanings cannot be implemented immediately by most participants. This fact is evidenced in the existence of the Stroop effect, that is, slower reaction times when word meanings and ink colors are incongruent rather than congruent (MacLeod, 1991). Posthypnotic suggestions, on the other hand, can efficiently enhance performance in the Stroop and other inhibition tasks. For instance, posthypnotic suggestions have been shown to decrease or eliminate the Stroop effect (Raz, 2005; Raz & Shapiro, 2002; Zahedi et al., 2017). Posthypnotic suggestions are usually elaborated rephrasings of standard task instructions or repetitions of critical elements thereof. For instance, a common posthypnotic suggestion used for the Stroop task is: "You will not be able to read the words presented on the monitor, and they will seem to you like words from a foreign language" (Zahedi et al., 2017, p. 72). This suggestion is very similar to the standard instruction: "do not read the words and only respond to the ink colors" (Zahedi et al., 2017, p. 72). Posthypnotic suggestions do not introduce new strategies, so how can they enhance performance in cognitive tasks?

1.2.2. Can Existing Theories of Hypnosis Explain the Effects of Posthypnotic Suggestions?

To understand the underlying mechanisms of posthypnotic suggestions, it is essential to first refer to existing theories of hypnosis. This section is not supposed to be an exhaustive review of existing hypnosis theories (for a complete review, see Manuscript 2) but instead presents an overview of those theories that try to explain the effects of posthypnotic suggestions. Traditionally, hypnosis has been defined by two different approaches. (I)The state account conceives hypnosis as an "altered" state of consciousness, which is characterized by increased concentration, dissociation, and increased suggestibility (Elkins, Barabasz, Council, & Spiegel, 2015). (II) The sociocognitive approach, on the other hand, emphasizes the top-down cognitive mechanisms utilized for responding to suggestions and psychosocial factors involved in the procedure (Green & Lynn, 2011; Jensen et al., 2017; Kihlstrom, 1985; Lynn & Green, 2011; Lynn, Green, et al., 2015; Lynn et al., 2019). For instance, the sociocognitive approach highlights the importance of the hypnotic situation, as it can dictates conformity to social expectations (Lynn, Green, et al., 2015). However, as Jensen et al. (2015) discussed, describing the existing theories as dichotomous gives a false account of the literature. More accurately, there is a spectrum of theories, many of which only partially overlap with the traditional accounts (for review, see Manuscript 2). However, regardless of their underlying assumptions, one should ask whether any of these theories can help us understand how posthypnotic suggestions affect performance in executive function tasks.

Interestingly, the only theory of hypnosis that tries to explain the observed effects of posthypnotic suggestions on performance in executive function tasks is the decoupling theory (Egner & Raz, 2007), which has been based on the state definition.

1.2.2.1. Dissociation and Decoupling Theory of Hypnosis

The dissociation theory (Woody & Bowers, 1994) is based on the concept of contention scheduling proposed by Norman and Shallice (1986). In essence, Norman and Shallice (1986) postulate that there is an intermediate domain of action, called contention scheduling, situated in between two extremes, that is, (I) reflexive schemata, which cannot be controlled at all, and (II) scripts that are flexibly controlled by the supervisory attentional system (SAS; Cooper & Shallice, 2000). Norman and Shallice (1986) assume that contention scheduling is in control in all situations where several “source schemata” compete with each other in “the determination of their activation value”. Conspicuously, source schemata are well-learned responses, and they are not related to new responses. Contention scheduling ensures that the schema, which first exceeds a certain threshold, will be selected. In non-demanding conditions, contention scheduling can operate without any input from the SAS. In contrast, in demanding conditions where the operation of contention scheduling in itself cannot result in correct and appropriate responses, the SAS has to interfere and ensure that the correct response will be selected by contention scheduling through implementing cognitive control and biasing activation of different schemata. Two pivotal examples are: (1) when a well-learned trigger-response contingency has to be suppressed in favor of a new response, and (2) when a new trigger-response contingency should be formed.

The dissociation theory was developed to explain alterations in the sense of agency during responding to hypnotic and posthypnotic suggestions (Woody & Bowers, 1994). Alteration in the sense of agency refers to the frequent observations that participants report a sense of semi-automaticity, effortlessness, and involuntariness when exerting hypnotic-suggestion-induced responses (Blakemore, Oakley, & Frith, 2003; Kirsch & Lynn, 1997; Lynn, Rhue, & Weekes, 1990). However, as Lynn et al. (1990) discussed, the experience of involuntariness does not imply a loss of control over the exerted responses. If encouraged, participants are able to resist the hypnotic-suggestion-induced responses (Lynn, Nash, Rhue, Frauman, & Sweeney, 1984; Spanos, Cobb, & Gorassini, 1985). Further, hypnotic-suggestion-induced responses are not automatic because they are resource-consuming (e.g., Tobis & Kihlstrom, 2010) and are executed by utilizing of top-down cognitive processes (Terhune, Cleeremans, Raz, & Lynn, 2017). Therefore, alterations in the sense of agency during hypnosis may be better explained as not attributing one's responses to the exertion of volitional effort (Lynn et al., 1990).

In the dissociation theory, the basic assumption is that hypnosis disables the SAS and therefore, participants will act only based on lower-level cognitive control processes, that is, contention scheduling. Thus, the sense of passivity occurs since higher cognitive control processes are disrupted, and participants cannot relate their actions to intention implementation or planning (Brown & Oakley, 2004; Jamieson & Woody, 2007; Woody & Bowers, 1994).

If under the influence of hypnosis, the SAS would be disabled, one expects that hypnotized participants cannot perform any executive function tasks. For instance, let us consider the Stroop task; according to the principles of contention scheduling, without any top-down control, the more robust schema (word reading) will be selected. For the weaker but task-relevant schema (color detection) to be chosen, cognitive control is required. Even though there are contradictory results regarding the effects of neutral hypnosis (i.e., hypnosis that does not contain any task-relevant suggestions) on task performance, but there is no doubt that participants can perform in executive function tasks under the influence of hypnosis similar to non-hypnotized conditions (e.g., Egner, Jamieson, & Gruzelier, 2005; Zahedi et al., 2017). For solving this contradiction, by using the conflict monitoring theory proposed by Botvinick et al. (2001), Egner et al. (2005) offered a revised version of the dissociation theory, called the decoupling theory. Botvinick et al. (2001) propose that cognitive control should be distinguished from monitoring processes at both anatomical and functional levels. Monitoring for cognitive conflicts takes place in the anterior cingulate cortex (ACC), whereas cognitive control processes are initiated in the dorsolateral prefrontal cortex (DLPFC). The decoupling theory claims that under the influence of hypnosis, the ACC will be disabled or decoupled from the rest of the SAS.

The decoupling account might explain why hypnotized participants can perform in the executive function tasks, but it cannot justify how task-relevant posthypnotic suggestions can enhance performance in cognitive tasks. Trying to solve this issue, Egner and Raz (2007) suggested that even though under the influence of hypnosis, there is “no internal generation and implementation of performance adjustments” (Egner & Raz, 2007, pp. 34-35), under the influence of posthypnotic suggestions participants can better follow externally presented strategies “due to the fact that task-processing is unencumbered by signals from internal performance monitoring” (p. 35). However, being unencumbered by monitoring signals does not answer how innate conflicts in inhibition tasks, for instance, the conflict between the word meanings and ink colors in the

Stroop task, can be resolved more efficiently. For answering this point, Egner and Raz (2007) suggested that the effects of posthypnotic suggestions can be similar to “contention scheduling”.

Two interpretations concerning the suggestion of Egner and Raz (2007) can be offered. (1) Posthypnotic suggestions instigate learning a new response in hypnotize participants. However, learning is the paragon of using top-down processes, which has been shown consistently to depend on the activation and coordination of cognitive control and cognitive monitoring (e.g., Gobel, Parrish, & Reber, 2011; van der Graaf, Maguire, Leenders, & de Jong, 2006), the latter of which Egner and Raz (2007) suggested to be disrupted during hypnosis. Consequently, the first interpretation of the decoupling theory has severe internal inconsistencies. (2) The decoupling account attributes improvements in performance to alterations in bottom-up processes. In other words, if internal cognitive control and cognitive monitoring processes are decoupled, and consequentially, executive functions are impaired, task-inappropriate, but automatic responses cannot be controlled by top-down modulations. Therefore, the only possible manner to make an automatic response ineffective without top-down regulation is by disrupting bottom-up processes. For instance, if posthypnotic suggestions in the Stroop task made participants temporarily dyslexic – dyslexia is the difficulty in reading in individuals who otherwise possess the cognitive functioning and education required for fluent reading and has been related to the disruption of activities in occipitotemporal visual cortices (Eden et al., 1996; Lobier, Peyrin, Pichat, Le Bas, & Valdois, 2014) – the weaker schema (color detection) could be selected without utilizing top-down regulation.

Concerning the second interpretation of the decoupling theory, it is not in line with empirical evidence. For instance, (1) it has been shown that enhancements in performance due to posthypnotic suggestions are related to more efficient utilization of executive functions, as evidenced by higher frontal theta and beta activations under the influence of posthypnotic suggestions compared to no-hypnosis or neutral hypnosis (Zahedi et al., 2017). (2) enhancements in performance cannot be attributed to the exertion of an automatic response, as "posthypnotic responding" is resource consuming (Tobis & Kihlstrom, 2010). Further, (3) many studies had shown that suggestions, regardless of being delivered during or outside of hypnosis, can enhance executive functioning (e.g., Palfi et al., 2020; Parris & Dienes, 2013), which indicates that the disabling of the ACC during hypnosis cannot explain the effects of posthypnotic suggestions.

In conclusion, none of the existing theories of hypnosis can offer a plausible, mechanistic explanation for the effects of task-relevant posthypnotic suggestions. Therefore, before using posthypnotic suggestions for studying executive functions, one needs to elucidate the driving mechanisms of task-relevant posthypnotic suggestions themselves.

1.3. Summary

In brief, the current project had two overarching and interdependent goals. (1) Several fundamental questions regarding the nature and structure of executive functions remained unanswered. That is, (a) Does unity explain executive functions better or diversity? (b) Are all subcomponents of inhibition implemented effortfully? (c) What do different versions of the Stroop task measure? Employing novel techniques and approaches are necessary for addressing these questions. One such experimental manipulation is using task-relevant posthypnotic suggestions for affecting executive functioning. (2) Even though post-hypnotic suggestions are repeatedly used to enhance performance in executive function tasks, the empirical evidence and existing theories cannot explain whether their effects are mediated through alterations in bottom-up or top-down processes. Hence, before using posthypnotic suggestions as an intervention for investigating executive functions, it is obligatory to understand how they affect performance. In other words, an experimental manipulation must affect the deployment of top-down processes in cognitive tasks to be relevant in studying executive functions' nature and structure. Consequently, in the current project, firstly, I tried to elucidate the underlying mechanisms of task-relevant posthypnotic suggestions and then employed them for addressing several long-lasting, fundamental questions regarding the nature and structure of executive functions.

2. Summary of Original Studies

In the following, I present a summary of the results of five studies, which were conducted to achieve the above-mentioned goals. In the first study, for elucidating whether the effects of posthypnotic suggestion are mediated by top-down or bottom-up processes, a task-relevant posthypnotic suggestion was used to enhance performance in a pure top-down component of executive functions, that is, updating in working memory. In the second study, a novel theory of hypnosis is suggested that can mechanistically explain fundamental hypnotic phenomena. In the third study, by applying confirmatory factor analysis and structural equation modeling to hypnotic-suggestibility scores, the proposed theory of hypnosis was tested empirically. In the fourth study, by employing task-relevant posthypnotic suggestions, loci of interference in the manual and vocal versions of the Stroop task were compared. Additionally, the neurocognitive correlates of the enhancement of suppression were elucidated. Finally, in the fifth study, using posthypnotic suggestions, food preferences for low- and high-calorie food items were manipulated to study the effortfulness of resolve at the time of implementation and further determine neurocognitive correlates of its enhancement.

2.1. Study 1: Can Posthypnotic Suggestions Boost Updating in Working Memory? Behavioral and ERP Evidence (Zahedi, Sturmer, & Sommer, 2020).

As mentioned above, there are many studies that have shown posthypnotic suggestions can enhance performance in inhibition tasks (for review, see Lifshitz et al., 2013). However, existing observations cannot answer whether the effects of posthypnotic suggestions are related to alterations in bottom-up or top-down processes. Part of this confusion is related to the nature of inhibition tasks. That is, an inhibition task, such as the Stroop task, can be enhanced both by alterations in the bottom-up processes (e.g., becoming temporarily dyslexic) and top-down modulations (e.g., learning a novel stimulus-response contingency and more efficient utilization of cognitive control processes). In contrast to inhibition tasks, enhancements in updating tasks can only be related to changes in top-down modulations. In updating tasks, different pieces of information are consecutively presented, and all of them have to be encoded and processed for solving the task. Nevertheless, these pieces of information are needed only for a short time, after which they become irrelevant and must be substituted by more recent information. Therefore, in contrast to inhibition tasks, suppressing a source of information by alterations in bottom-up processes will be of no help in updating tasks. Further, as updating tasks require different responses depending on highly variable conditions, using inflexible lower-level schemata that cannot be controlled or adapted are also not able to enhance performance. Therefore, if posthypnotic suggestions can improve performance in updating tasks, it will strongly indicate that alterations in top-down modulations and not bottom-up processes are the driving mechanism of task-relevant posthypnotic suggestions' effects.

The second goal of Study 1 was to elucidate the neural correlates of working memory load in updating tasks. This step was necessary as most neurocognitive studies of updating have mainly used the N-back task (e.g., Brouwer et al., 2012; Dong et al., 2015; Evans et al., 2011; Nakao et al., 2012; Scharinger et al., 2017; Watter et al., 2001), which has been disputed as a pure measure of updating (Miyake et al., 2000; Schmiedek, Hildebrandt, Lovden, Wilhelm, & Lindenberger, 2009). Therefore, before generalizing ERP results from the N-back task to the updating function, they should have been cross-validated by another task measuring updating (Scharinger et al., 2017) to rule out task-specificity rather than function-specificity.

Therefore, in Exp. 1 of Study 1, we used a tone-monitoring task, which is a pure measure of updating in working memory (Miyake et al., 2000), in order to investigate updating load effects and their neural correlates. In the tone-monitoring task, different syllables are consecutively presented in random order, requiring a response to every *N* (e.g., four in our study) presentation of a given syllable. In Exp. 1, 19 healthy adults participated in the tone-monitoring task while ERP data were recorded during task completion. Together, the results of Exp. 1, in line with the results of studies using the N-back task, showed several ERP components, including N1, N2, P2, P3, and the frontal and posterior old/new component, were sensitive to updating load.

In Exp. 2, based on the results of Exp. 1, we decide to use a tone-monitoring task for investigating the underlying mechanisms of posthypnotic suggestions' effects on updating tasks. However, for scrutinizing the specificity of the posthypnotic suggestion's effects, Load 1 was included in the tone-monitoring task. Load 1 is superficially isomorphic with the other load conditions, as it requires the same auditory input and manual output; however, it consists of a simple counting task and does not require the updating function. We tested 18 high-hypnotic-suggestible healthy adults with the tone-monitoring task while ERP data were recorded. Further, a counterbalanced repeated-measure design was used, with two sessions, that is, the posthypnotic suggestion and no-hypnosis sessions. The only difference between the two sessions was that in the posthypnotic session but not the no-hypnosis session, participants received hypnosis, including a posthypnotic suggestion. The posthypnotic suggestion was designed to be an elaborated rephrasing of the task instructions to prevent introducing a new strategy for task completion. We used only high-hypnotic-suggestibles since it is commonly held that posthypnotic suggestions affect them more substantially (Green & Lynn, 2011; Jones & Spanos, 1982; Lynn et al., 2019; Woody & Barnier, 2008). The high-hypnotic-suggestibles recruited for Exp. 2 were invited from a poll of

157 participants, who were screened by the German version (Bongartz, 1985) of the Harvard group of hypnotic susceptibility scale (HGSHS; Shor & Orne, 1962; Shor & Orne, 1963).

The results of Exp. 2 indicated that posthypnotic suggestion, relative to the no-hypnosis condition, enhanced performance in the tone-monitoring task. Notably, for Load 1 in Exp. 2, the performance was not significantly affected by the posthypnotic suggestion. The absence of significant posthypnotic suggestion's effects in Load 1 supports the selectivity of the posthypnotic suggestion to updating requirements. In other words, the posthypnotic suggestion did not affect performance in general, but specifically the updating function. Further, these enhancements were correlated with the increase in P2 and P3 amplitudes, indicating the proactive recruitment of control-related attention (e.g., Dunn, Dunn, Languis, & Andrews, 1998; Han, Liu, Zhang, Jin, & Luo, 2013) and updating-related cognitive control processes (Donchin & Coles, 1988; Polich, 2007), respectively. The posthypnotic suggestion also reduced updating load effects in the posterior recognition (old/new) component, suggesting that demands on working memory buffers were diminished (Rugg & Curran, 2007; Wilding & Ranganath, 2011). Noticeably, the load-independent increase in recruitment of attention- and cognitive-control-related processes was followed by the decrease in subsequent working memory buffer activity. This fact indicates that the enhancement in updating was related to the improved deployment of proactive control that decreased the need for reactive control. In contrast to reactive control, proactive control processes are recruited in advance, regardless of their necessity in the forthcoming situation (Braver, 2012; Braver, Paxton, Locke, & Barch, 2009). Noticeably, proactive control is related to sustained preparedness and maintenance of goal-related information in the lateral prefrontal cortex (LPFC) in contrast to reactive control that reflects stimulus-driven goal reactivation (Braver, 2012; Braver et al., 2009).

In conclusion, the results of Study 1 showed that (1) load effects in the tone-monitoring task consistently resemble neurocognitive effects reported in the N-back and other memory tasks. (2) The enhancements in executive functioning due to task-relevant posthypnotic suggestions are related to the improved deployment of top-down modulations and cannot be attributed to alternations in bottom-up processes.

2.2. Study 2: How Hypnotic Suggestions Work – Critical Review of Prominent Theories and a Novel Synthesis. (Zahedi & Sommer, in prep).

The aim of Study 2 was to either find an existing theory of hypnosis or propose a novel one that can account for key hypnotic phenomena, including the effects of task-relevant posthypnotic suggestions on executive functioning.

Study 2 consists of three parts. First, we procedurally described hypnosis, hypnotizability, and effects of hypnotic and posthypnotic suggestions on behavior, perception, cognition, and the subjective sense of agency. Then we provided a comprehensive systematic and comparative review of the most prominent theories of hypnosis. In this systematic review, theories are explained and evaluated based on a set of clearly defined criteria, focusing on their adequateness, parsimoniousness, and falsifiability. These criteria loosely follow those outlined by philosophers of science like Karl Popper (1971). Although there is a plethora of theories that try to account for pivotal hypnotic phenomena, we believe that our systematic review demonstrated, none of them can fully explain all critical hypnotic phenomena.

In the final part, aiming to remediate the shortcomings of existing theories, we proposed a novel theory of hypnosis, called the simulation-adaptation theory of hypnosis (SATH). In short, SATH claims that there are three top-down cognitive processes, which can be employed by a cooperative and willing participant to successfully exert hypnotic and posthypnotic suggestion-induced responses. These basic top-down processes are (1) *cognitive-simulation* (for review, see Hesslow, 2002)*:* imagining a stimulus, which can lead to perceptual and neural responses similar to experiencing the corresponding stimulus in reality. (2) *sensory-adaptation* (for review, see Frank, 2016; Lopresti-Goodman, Turvey, & Frank, 2013): top-down downregulation of sensory input, which can cause alterations in perception of stimuli, including agnosia. (3) *mental practice* (cf. Zahedi, Sturmer, et al., 2020): mentally simulating a novel situation employed as a practice environment, where new strategies are practiced to learn a new, context-dependent trigger-response contingency. These processes can be employed to different extents and in different combinations, depending on the individual capabilities of participants.

Noteworthy, in contrast to the dissociation/decoupling account, SATH argues that the effects of task-relevant posthypnotic suggestions are related to the enhanced utilization of top-down processes. For instance, let us consider the effects of posthypnotic suggestions in inhibition tasks. SATH's suggestion implies that posthypnotic suggestions cause (1) learning new responses and making them semi-automatic, so they can compete with automatic, task-irrelevant responses, and (2) faster detection of conflicts and enhanced deployment of inhibition to suppress irrelevant schemata. Hence, in contrast to the decoupling account, SATH predicts that under the influence of task-relevant posthypnotic suggestions, cognitive monitoring processes are in close contact with cognitive control processes. Further, performance improvements are related to increased deployment of proactive control processes, eliminating the need for reactive control.

In conclusion, in Study 2, it has been shown that none of the existing theories of hypnosis can explain all pivotal hypnotic phenomena. Consequently, a novel theory of hypnosis (SATH) was proposed, which can mechanistically explain all key hypnotic phenomena, including the effects of task-relevant posthypnotic suggestions on executive functioning.

2.3. Study3: Is There a G-factor in Hypnotic Suggestibility? Confirmatory Factor Analysis of the Harvard Group Scale of Hypnotic Suggestibility. (Zahedi & Sommer, in prep).

The aim of Study 3 was to test SATH empirically. In doing so, SATH was used for addressing one of the contentious issues in the field of hypnosis regarding the structure of hypnotic-suggestibility scores. That is, we tried to elucidate the number and nature of latent factors that are required for modeling hypnotic-suggestibility scores.

Noteworthy, there is an unwavering consensus between researchers in the field of hypnosis about the existence of substantial within- and between-subject variability in responding to (post)hypnotic suggestions (for review, see Kirsch, 1997; Lynn et al., 2019; Terhune et al., 2017). Commonly, for quantifying individual differences in responsiveness to suggestions, standardized scales of hypnotic susceptibility, such as the HGSHS (Bongartz, 1985; Shor & Orne, 1962; Shor & Orne, 1963; Woody & Barnier, 2008), are used. However, these scales are not measuring (a) general suggestibility: the capability to respond to suggestions regardless of hypnosis, or (b) hypnotizability: the increase in general suggestibility due to the hypnosis induction, per se (Kirsch, 1997). Instead, these scales are measuring a mixture of general suggestibility and hypnotizability that can be called hypnotic-suggestibility (Kirsch, 1997). SATH, based on existing empirical evidence, suggests that (1) suggestibility or, more accurately, suggestibilities are related to top-down cognitive functions (for review, see Terhune et al., 2017), (2) hypnotizability, however, is more strongly associated with psychological factors, such as willingness and openness (for review, see Lynn et al., 2019). Considering these points, one might expect that two sources of variance simultaneously affect hypnotic-suggestibility scores. This argument highlights the importance of using bifactor modeling (Reise, 2012) for analyzing the structure of hypnotic-suggestibility scores.

Previous studies investigating the structure of hypnotic-suggestibility scales (e.g., McConkey, Sheehan, & Law, 1980; Oakman & Woody, 1996; Piesbergen & Peter, 2006) had used data-driven exploratory factor analysis (EFA). Even though EFA is a necessary first step as it does not rely on any theory, but it has two critical shortcomings (Coulacoglou & Saklofske, 2017; Harrington, 2009). (I) Its data-driven nature hinders any firm interpretation of latent factors or their indicators in the selected model (Coulacoglou & Saklofske, 2017; Harrington, 2009). (II) In EFA, it is only possible to test basic multifactor but not bifactor models (Eid, Geiser, Koch, & Heene, 2017; Eid, Krumm, Koch, & Schulze, 2018; Reise, 2012).

In Study 3, for compensating shortcomings of previous EFAs, we use SATH to derive appropriate hypotheses necessary for employing confirmatory factor analysis (CFA) and structural equation modeling (SEM) for analyzing hypnotic-suggestibility scores. The HGSHS, one of the canonical examples of hypnotic-suggestibility scales, was used to obtain hypnotic-suggestibility scores from a sample of 477 volunteers. Based on SATH, several models were suggested and tested with CFA. Two more consequential models were (I) a basic multifactor model, closely corresponding to the dominant solution of previous EFAs (e.g., McConkey et al., 1980), and (II) a bifactor model, consisting of a G-factor tapping into hypnotizability and three correlated specific grouping factors measuring different suggestibilities. Noticeably, suggestibilities are distinguished as each requires a unique combination of three top-down cognitive functions proposed by SATH, that is, cognitive-simulation, sensory-adaptation, and mental practice/problem-solving. The results showed that HGSHS scores, as predicted by SATH, were best explained by the bifactor model. Further, structural equation modeling of causal pathways between latent factors revealed that the outcome of the suggestions, requiring a combination of cognitive-simulation and sensory-adaptation, can predict responses to other suggestions. These results have several critical implications for future applications of hypnotic-suggestibility scales in clinical and experimental settings. One of these implications related to the utilization of posthypnotic suggestions as an experimental manipulation will be discussed in section 3.3.

In conclusion, Study 3 showed that a bifactor model, proposed based on the hypotheses derived from SATH, can adequately explain the variance in hypnotic-suggestibility scores. These results, in turn, provided empirical support for SATH and its postulation that three top-down processes are employed by willing and cooperative participants for responding to suggestions

2.4. Study 4: Common and Specific Loci of Stroop Effects in Vocal and Manual Tasks, Revealed by Event-Related Brain Potentials and Posthypnotic Suggestions. (Zahedi, Abdel Rahman, Sturmer, & Sommer, 2019).

In Study 4, we had two overarching goals. First, we wanted to find the neural correlates of the inhibition function's enhancements. And second, we wanted to compare the loci of interference in the two versions of the Stroop task, that is, the manual and the vocal task versions. For achieving these aims, similarities and differences in ERPs of these two tasks and the neurocognitive effects of task-relevant posthypnotic suggestions on them were investigated.

We tested 16 high-hypnotic-suggestible healthy adults in a counterbalanced design with two sessions, that is, no-hypnosis and posthypnotic suggestion sessions. In both sessions, both versions of the Stroop task were administered while ERP data were recorded. Similar to Study 1, the only difference between the two sessions was that in the posthypnotic session, prior to task completion, participants were hypnotized and received a posthypnotic suggestion. The posthypnotic suggestion was designed to be an elaborated rephrasing of the task instructions and do not introduce any new strategies for task completion. The order of the tasks was counterbalanced across participants but fixed for each participant in both sessions. In Study 4, similar to Study 1 (Zahedi, Sturmer, et al., 2020), we used only high-hypnotic-suggestibles. The high-hypnotic-suggestibles were recruited from a poll of 122 participants, who were screened by the German version (Bongartz, 1985) of the HGSHS (Shor & Orne, 1962; Shor & Orne, 1963). Considering the ERP data in the vocal version, the problem of articulation artifacts, typically arising during overt naming, was resolved by applying RIDE (Ouyang et al., 2016). The benefit of RIDE is that it can separate the brain-derived ERPs from overlapping articulations artifacts. Hence, in Study 4, we were able to also use ERP data for addressing the similarities and differences between the two Stroop versions.

The results of the psychometric measurements showed that the Stroop effect ($RT_{\ incongruent} - RT_{congruent}$) in the vocal version was twice its manual counterpart, and the posthypnotic suggestion strongly reduced both effects by a similar amount. In the ERPs, our articulation-artifact-corrected results showed enhancements in performance caused by the posthypnotic suggestion were correlated with the increase of N1 amplitudes and the decrease of N2 amplitudes. These results possibly indicate that the posthypnotic suggestion improved the initial recruitment of cognitive control processes, which was followed by diminished demands on the conflict monitoring processes (Coderre, Conklin, & van Heuven, 2011; Coderre & van Heuven, 2014). Additionally, the posthypnotic suggestion increased the P300 amplitudes in congruent (significantly) and incongruent trials (marginally). P300 is positively correlated with incorporating cognitive-control-related processes (Fonken et al., 2020; Polich, 2007). Additionally, the posthypnotic suggestion modulated N400, a negative-going parieto-central deflection that is typically larger in response to incongruent than congruent trials. N400 is considered as the neural marker of semantic processing (Hanslmayr et al., 2008; Liotti et al., 2000; West & Alain, 1999). Together, the changes in P300 and N400 possibly indicate that the posthypnotic suggestion's effects were mediated through enhancing proactive executive control over lexico-semantic conflicts. Finally, response-locked ERPs revealed a task-specific Stroop effect in the vocal task over left-inferior frontal and parietal scalp sites, which was absent in the manual version and was not modulated by the posthypnotic suggestion.

In conclusion, our results indicated that even though the manual and vocal versions are both tapping into the inhibition function, they are not identical. These two versions have a common semantic locus of interference during reading. However, there was an exclusive locus of interference during response production in the vocal version, which was absent in the manual version. Furthermore, the enhancements due to the posthypnotic suggestion were related to proactive recruitment of cognitive control processes, which decreased the necessity of reactive control.

2.5. Study 5: Modification of Food Preferences by Posthypnotic Suggestions: An Event-Related Brain Potential Study. (Zahedi, Luczak, & Sommer, 2020).

In Study 5, we investigated whether posthypnotic suggestions can also improve the resolve function, and if so, what are the neural correlates of these enhancements. For achieving these aims, we employed posthypnotic suggestions to enhance preferences for low-calorie food preferences, and by contrast, make high-calorie food items less appealing.

In Study 5, 20 medium- and high- hypnotic-suggestible participants were hypnotized at the beginning of the session and received a posthypnotic suggestion that focused on increasing the preference for low-calorie food items. After the termination of hypnosis, our task-set was administrated once when the posthypnotic suggestion was activated and once when deactivated while ERP data were recorded. The task-set consisted of two tasks: the food-face classification and the Go-NoGo task. The order of conditions was counterbalanced across participants, but the order of tasks in the task-set was fixed. In the food-face classification, pictures of food items and faces were consecutively presented on the monitor. Participants were instructed to identify whether a given picture shows a food item or face by pressing corresponding buttons. Notably, the calorie-unrelated task of explicitly classifying stimuli into food or face categories aimed to distract participants from forming hypotheses regarding the experimenters' intentions. Hence, the food-face classification possibly measures implicit changes in food preference induced by the posthypnotic suggestion. In the Go-NoGo task, which was used to measure the effects of resolve on the inhibition function, participants were instructed to choose those items they did not wish to put in their salad. Therefore, high- and low-calorie food items were Go (frequent) and NoGo (infrequent) trials, respectively. Considerably, in Study 5, based on a call from Jensen et al. (2017), and in line with the results of Study 3, we recruited both high- and medium-hypnotic-suggestibles to increase the generalizability of our results.

The food-face classification results showed that even though when the posthypnotic suggestion was deactivated high- compared to low-calorie food items provoked higher P1 amplitudes, these differences were eliminated when the posthypnotic suggestion was activated. These changes were mainly due to the increased P1 to low-calorie items. P1 amplitude has been reported to be larger in response to reward-associated than neutral or punishment-associated stimuli (Hickey, Chelazzi, & Theeuwes, 2010; Schacht, Adler, Chen, Guo, & Sommer, 2012). Therefore, the modulation of P1 amplitude by the posthypnotic suggestion possibly indicates that the intervention successfully altered food-preferences.

By considering the food-face classification results, we utilized the Go-NoGo task to investigate behavioral and neural correlates of resolve. The Go-NoGo task results showed that participants were faster in rejecting salad-inappropriate high-calorie food items in the posthypnotic suggestion active compared to inactive condition. Further, the enhancements in performance were correlated with the decrease in NoGo-N2 amplitudes and the increase in Go- and NoGo-P3 amplitudes. These results possibly indicate that the posthypnotic suggestion enhanced performance by increasing the recruitment of proactive control processes, which subsequently decreased the need for reactive control. Finally, the posthypnotic suggestion increased the amplitude of the late Go-P3 component. This result possibly shows that classification of high-calorie items was facilitated due to increased response monitoring under the influence of the posthypnotic suggestion (Fonken et al., 2020; Polich, 2007).

In conclusion, the results of Study 5 indicate that changes in preferences for different food-items improved resolve, which in turn enabled participants to handle the conflict between bigger-slower versus smaller-faster rewards better. Noticeably, implementing resolve was effortful, as indicated by the increase in P300 amplitudes. Finally, the resolve function was enhanced by posthypnotic suggestions due to improved deployment of proactive cognitive control processes.

3. General Discussion

This project had two interdependent overarching goals. (1) I wanted to investigate how task-relevant posthypnotic suggestions can enhance executive functioning in different cognitive tasks. (2) Using appropriate posthypnotic suggestions, I tried to address several fundamental questions concerning the structure and nature of executive functions. To this end, five studies were conducted. In Study 1, task-relevant posthypnotic suggestions were used to improve a pure component of executive factions, that is, updating. The results indicated that posthypnotic suggestions improved updating in the working memory through affecting top-down processes. In other words, posthypnotic suggestions helped participants to learn a novel stimulus-response contingency and deploy their cognitive control processes more efficiently. In Study 2, a novel theory of hypnosis was proposed that, in contrast to other theories, can cover all fundamental hypnotic phenomena, including the effects of task-relevant posthypnotic suggestions on executive functioning. Based on SATH, task-relevant posthypnotic suggestions enabled hypnotized participants to utilize a mentally simulated environment for practicing a strategy presented by the hypnotist. In Study 3, SATH was tested empirically by investigating its hypotheses regarding the structure of hypnotic-suggestibility scores. Study 3 showed that a bifactor model proposed by SATH explains variance in HGSHS scores better than the dominant solution of previous EFAs (e.g., McConkey et al., 1980; Oakman & Woody, 1996; Piesbergen & Peter, 2006). Study 4, using posthypnotic suggestions for comparing manual and vocal versions of the Stroop task, showed that the vocal task version is more taxing than the manual version, as it engages an extra response-production-related locus of interference. Finally, in Study 5, using posthypnotic suggestions to affect preferences for different food-categories, the effortfulness of implementing resolve was investigated. The results revealed that the implementation of resolve is, similar to suppression, strenuous. Additionally, Studies 4 and 5 indicated that improvements in both suppression and resolve are related to the increased deployment of proactive cognitive control processes, decreasing the necessity of reactive control. In the following, firstly, the obtained results will be discussed according to each of our questions, and then, implications, limitations, and future perspectives will be considered.

3.1. Mental Practice Can Explain Different Aspects of Task-Relevant Posthypnotic Suggestions' Effects

The first aim of the current project was to discern driving mechanisms of task-relevant posthypnotic suggestions' effects. Study 1 showed that the effects of posthypnotic suggestions could not be attributed to alterations in bottom-up processes. Instead, changes in top-down modulations must be propelling posthypnotic suggestions' effects since posthypnotic suggestions can also affect updating in working memory, a pure top-down component of executive functions. In addition, Studies 1, 2, and 3 proposed mental practice as the driving mechanism of task-relevant posthypnotic suggestions' effects in an attempt to specify the top-down processes affected by them. And finally, Studies 4 and 5 corroborated this account by showing that the effects of posthypnotic suggestions are related to increased deployment of proactive control and more efficient implementation of control processes. Noteworthy, even though there is no consensus in the literature about top-down processes that are influenced by post(hypnotic) suggestions, most researchers agree that the effects of suggestions should be attributed to changes in top-down modulations (for review, see Landry, Lifshitz, & Raz, 2017; Terhune et al., 2017), and empirical evidence corroborate this account (e.g., Landry, Da Silva Castanheira, Sackur, & Raz, 2021; Lush et al., 2020; Palfi et al., 2020; Tobis & Kihlstrom, 2010; Zahedi et al., 2017).

Assuming mental practice as the mechanism that drives the effects of posthypnotic suggestions can adequately explain existing observations in the literature. Let us consider several critical examples; (1) suppose posthypnotic suggestions' effects are related to mental practicing and not any unique characteristics of hypnosis; in that case, hypnosis without task-relevant hypnotic and posthypnotic suggestions (i.e., neutral hypnosis) must not affect performance in executive function tasks. This prediction is in line with empirical evidence that neutral hypnosis, if not destructive, is unable to enhance executive functioning (e.g., Egner et al., 2005; Sheehan, Donovan, & MacLeod, 1988; Zahedi et al., 2017). (2) If the same suggestions are presented outside of hypnosis, they must have comparable effects to posthypnotic suggestions. Again, existing observations corroborated that task-relevant suggestions, inside or outside of hypnosis, can similarly affect perception and cognition (e.g., Mazzoni et al., 2009; McGeown et al., 2012; Palfi et al., 2020; Parris, Dienes, & Hodgson, 2013). (3) As the effects of posthypnotic suggestions are related to mental practice, they must be effective in improving many different functions and not only inhibition. In line with Study 1, other researchers also reported that posthypnotic suggestions could affect other functions besides inhibition (e.g., Landry et al., 2021; Lindelov et al., 2017). (4) Noteworthy, strategies suggested in posthypnotic suggestions are commonly similar to those offered by task instructions (e.g., Iani et al., 2009; Iani et al., 2006; Parris et al., 2012; Raz et al., 2005; Raz et al., 2006; Zahedi et al., 2017). Consequently, posthypnotic suggestions' effects cannot be attributed to using a different strategy compared to no-hypnosis conditions but implementing the same strategy more robustly and efficiently. Therefore, assuming mental practice as the driving mechanism of the posthypnotic suggestions' effects can congruently explain existing observations in the literature.

Two points, however, should be discussed about SATH's proposition. Firstly, if mental practice enhances performance in both inhibition and updating tasks, standard practice should also enhance these functions. Regarding the inhibition function, one should notice that even though inhibition tasks are resilient to practice, they are not immune. Let us consider Stroop effects; many studies showed that Stroop effects can be significantly reduced by practice in participants of almost every age (e.g., Dulaney & Rogers, 1994; Protopapas, Vlahou, Moirou, & Ziaka, 2014). Intriguingly, according to MacLeod (1991), Ridley Stroop himself was the first to report the effects of practice on Stroop task performance. He observed that after several days of extensive training, the response of color detection becomes semi-automatic, and there can be even a reversed Stroop effect. In other words, in Ridley Stroop's study, when after extensive training, the task was changed from detecting colors to reading words, the ink colors interfered with the word meanings (MacLeod, 1991). Notably, it has been argued that the mechanism underlying changes in Stroop effects due to practice is related to developing a new semi-automatic response of color detection, which can compete with the previously established automatic response of word reading.

Concerning updating in working memory, it has also been shown that extensive training can enhance performance in updating tasks (Diamond & Ling, 2016). Notably, enhancements in the updating function due to extensive practice cannot be attributed to the increased working memory capacity (Diamond & Ling, 2016), indicating that forming a well-learned trigger-response contingency had empowered participants to utilize their cognitive control more efficiently. Therefore, not only practice can improve both updating and inhibition, but the effects of practice are mediated by top-down processes and are closely related to mechanisms propose by SATH to explain posthypnotic suggestions' effects.

The second point is related to the possibility of activating and deactivating effects of posthypnotic suggestions. One might ask if mental practice is the driving mechanism of posthypnotic suggestions, why are their effects restricted to the condition, during which they are activated, and vanish after they are deactivated? Learning can be context-dependent, especially if learned responses are not extensively practiced. For instance, Abrahamse and Verwey (2008) have shown that changing the context causes participants to inhibit learned responses. Further, Ruitenberg, De Kleine, Van der Lubbe, Verwey, and Abrahamse (2012) showed that changing contextual cues can be detrimental to learned responses, especially if practice time is limited. As discussed above, posthypnotic suggestions do not result in an automatic response, and therefore, contextual dependencies are unavoidable. Consequently, it is predictable that the enhancements in performance due to posthypnotic suggestions will be present only when they are activated and vanish when deactivated.

3.2. Unity and Diversity Executive Functions

Now that the driving mechanisms of posthypnotic suggestions are elucidated, the results of Studies 1, 4, and 5 can be used to address unity versus diversity of executive functions. In Table 1, a summary of the neural correlates of executive functions' enhancements due to the application of task-relevant posthypnotic suggestions are presented. Notably, in each function, the enhancement is correlated with some load-independent unidirectional changes in early ERP components, such as P1, N1. N2, and P2. These changes are followed by load-dependent modulations in subsequent ERP components, such as N400, late Go-P3, and the posterior old/new component.

However, one should notice that the above-mentioned ERP components are related to vastly different cognitive functions. Regarding early ERP components, P1 has been associated with the processing of rewarding value of stimuli (Hickey et al., 2010; Schacht et al., 2012). N1, on the other hand, is related to the initial recruitment of cognitive control processes (Coderre et al., 2011; Coderre & van Heuven, 2014). N2 is a neural marker of conflict detection (Enriquez-Geppert et al., 2010; Folstein & Van Petten, 2008; Gajewski & Falkenstein, 2013; Yang et al., 2014; Yuan et al., 2011). And finally, P2 is related to incorporating attentional resources (e.g., Dunn et al., 1998; Han et al., 2013). Concerning late ERP components, N400 is the ERP marker of semantic processing (Hanslmayr et al., 2008; Liotti et al., 2000; West & Alain, 1999). Late Go-P3, however, has been related to response monitoring (Fonken et al., 2020; Polich, 2007). And finally, the posterior old/new component has been associated with retaining a mental representation in working memory buffers (Rugg & Curran, 2007; Wilding & Ranganath, 2011). Therefore, the unique ERP components affected by the enhancement of each function can corroborate the diversity proposition. However, the fact that P3 is affected by the improvements of all executive functions indicates that these top-down processes share at least one common neural system. Interestingly, P3 is the ERP component that has been repeatedly associated with the recruitment of executive functions (Donchin & Coles, 1988; Polich, 2007).

Table 1. The Summary of the neural correlates of enhancements in executive functioning due to the application of task-relevant posthypnotic suggestions.

Executive Function	Task	ERP component		Direction of Modulation [a]
Updating	Tone-monitoring	Early component	P2	$\Delta\uparrow$
		Late component	P3	$\Delta\uparrow$
			Posterior Recognition Component	ΔX
Inhibition: Suppression	Stroop	Early component	N1	$\Delta\uparrow$
			N2	$\Delta\downarrow$
		Late component	P3	ΔX
			N400	ΔX
Inhibition: Resolving		Early component	P1	ΔX
			N2	$\Delta\downarrow$

Executive Function	Task	ERP component		Direction of Modulation [a]
	Food-face classification; Go-NoGo	Late component	P3	$\Delta\uparrow$
			Late Go-P3	ΔX

Note: [a] $\Delta\uparrow$ and $\Delta\downarrow$ designate a load-independent increase or decrease in ERP amplitudes, respectively. In contrast, ΔX denotes a load-dependent modulation of a given ERP component.

A possible interpretation of the current results, which can solve the above-mentioned conundrum, is that even though executive factions are distinguishable, there is a central processing unit on which all of them depend. In other words, each executive function relies on a unique set of early processes that break down the complete task into processable pieces. These mini-tasks are parceled and sent to the central unit, activation of which is marked by the onset of the P3 component. Afterward, when these mini-tasks are adequately processed, the output of these processes will be sent to late processing units, whose activities are tightly related to response production. That is, one can suggest a shared *attentional system*, which is activated whenever the existing repertoire of stimulus-response contingencies are not appropriate or sufficient for the task at hand.

The proposition of a shared attentional system can explain the previous findings at both the cognitive and neural levels. For example, if we assume a shared attentional system, it should incorporate task-specific functions or systems based on the particular requisites of the task at hand. For instance, the visuospatial sketchpad and the phonological loop are engaged for visual versus auditory tasks, respectively (Baddeley, 2003). The incorporation of different cognitive systems predicts that tasks measuring different functions should load on distinguishable latent factors. However, executive functions rely on both function-specific early processes, marked by unique ERP components, and a shared central cognitive unit, activation of which triggers P3. Therefore, at the cognitive level, one expects executive functions to be correlated, despite loading on different factors. The results of Miyake et al. (2000) corroborate this prediction. They found that a three-factor model with strongly correlated latent factors could explain psychometric data obtained from 9 different executive function tasks better than one- or two-factor models.

The existence of a shared attentional system can also answer why in studies using adolescent/child samples, CFAs favor a unidimensional model, but in adults, a multifactor one (Karr et al., 2018). It can be stated that in adolescents/children, whose central unit capacity is not fully developed yet (Best, Miller, & Jones, 2009), the differences between executive functions will be overshadowed by the existence of a bottleneck in the central unit. Hence, in these samples, a unidimensional model explains the distribution of executive functions better. However, in adults, who are fully developed, differences between early-stage processes are more critical in defining each executive function rather than the central unit capacity. Consequently, a multifactor model will be better for explaining the variance in their performance.

At the neural level, assuming a shared attentional system predicts that employing different executive functions would be correlated with both function-specific neural systems and a shared frontocentral neural system. This prediction is also in line with findings of previous studies and metanalyses. (Collette et al., 2005; Niendam et al., 2012; Rottschy et al., 2012; Wager & Smith, 2003; Yuan & Raz, 2014). Notably, the shared foci of activation between different executive functions observed by previous neuroimaging studies have considerable overlap with the topographies of the P300 component, observed in Studies 1, 4, and 5. For instance, Collette et al. (2005) found that all executive functions rely on the activation of the right intraparietal sulcus, the left superior parietal gyrus, and the left lateral prefrontal cortex. These frontoparietal foci of activation appreciably overlap with the frontocentral topographies of P3 observed in our studies.

3.3. The Manual and Vocal Versions of The Stroop Task are Different

The overarching aim of Study 4 was to compare the manual and vocal versions of the Stroop task. For reaching this aim, performance and ERP data obtained in the no-hypnosis and the posthypnotic suggestion conditions were employed. The psychometric results of the no-hypnosis session showed that the Stroop effect (i.e., the difference in performance between incongruent versus congruent trials) in the vocal version was twice its manual counterpart. This finding was in line with previous studies comparing the vocal and manual versions (Liotti et al., 2000; Redding & Gerjets, 1977). Notably, even though the posthypnotic suggestion reduced the Stroop effect in both manual and vocal versions by a similar amount, the Stroop effect in the vocal version was still substantially bigger compared to the manual version under the influence of the posthypnotic suggestion.

For investigating sources of differences between the two task versions, it is necessary to consider the ERP results. Both the manual and vocal versions evoked large N400 ERP effects between incongruent and congruent trials, reflecting the existence of semantic interference in both tasks (Hanslmayr et al., 2008; Liotti et al., 2000; West & Alain, 1999). Further, under the influence of the posthypnotic suggestion, N400 was attenuated in both task versions. However, analysis of N400 in the no-hypnosis condition and its modulation by the posthypnotic suggestion did not reveal a clear dominance of the vocal over the manual version. However, there was a discrepancy between the two task versions in response-lock ERPs, indicating a response-related conflict in the vocal version that was absent in the manual version. This response-related conflict was present at the left inferior-frontal (including Broca's area) and parietal (including Wernicke's area) scalp regions, which have been related to phonological retrieval and syllabification (Indefrey, 2011; Indefrey & Levelt, 2004). Noticeably, the conflict component with parietal ERP distribution was not affected by the posthypnotic suggestion, whereas the conflict with left inferior-frontal manifestation was marginally mitigated by the posthypnotic suggestion. This result possibly indicates that even though the posthypnotic suggestion reduced conflict in the language production layer in the vocal version, it could not eliminate it.

By considering both psychometric and ERP results, it is possible to conclude that even though both task versions cause semantic interference, and therefore, require inhibition implementation for overriding incorrect responses with correct ones (Botvinick et al., 2001; Botvinick, Cohen, & Carter, 2004), the vocal and manual task versions are not identical. That is, a response-related locus of interference that exists in the vocal version is absent in the manual version. Further, as this response-related locus of interference is not affected by the posthypnotic suggestion, it is comprehensible why the differences between the two task versions are persistent and do not vanish even under the influence of the posthypnotic suggestion.

A critical implication of these findings for the theories that try to account for the Stroop effect is that in the Stroop task, perceptual input from two sources of information, that is, word meanings and ink colors, interact with each other at multiple loci. Therefore, any account that focuses only on one locus of interference, for instance, the lexico-semantic level (e.g., Dell, 1986; Levelt, Roelofs, & Meyer, 1999; Shitova, Roelofs, Schriefers, Bastiaansen, & Schoffelen, 2017) or the response-production level (Mahon, Costa, Peterson, Vargas, & Caramazza, 2007), and neglect the others cannot fully explain the Stroop effects. This conclusion is in line with existing empirical evidence (Banich, 2019).

3.4. No Matter Resolving or Suppressing, Inhibition Implementation is Effortful

Studies 4 and 5 showed that posthypnotic suggestions could enhance inhibition. In both Studies, posthypnotic suggestions decreased N2 amplitudes independent of task load and subsequently increased P3 amplitudes in conditions that cognitive control was required. These ERP changes possibly indicate an increased deployment of proactive control processes, which, in turn, decreased the desideratum for reactive control (Braver, 2012; Braver et al., 2009). However, in these two studies, inhibition was improved by vastly different approaches. In Study 4, the posthypnotic suggestion was focused on boosting suppression of a prepotent but task-irrelevant response in the Stroop task so that the task-relevant response could be exerted more efficiently and proficiently. In Study 5, on the other hand, the posthypnotic suggestion concentrated on increasing preferences for low-calorie food items and, by contrast, decreasing the preferences for high-calorie food. When the posthypnotic suggestion was activated, implementing new preferences caused participants to reject high-calorie food items faster than when the posthypnotic suggestion was deactivated. In other words, when participants were suggested to form a novel motivational contingency, high-calorie food items could be rejected easier. In Study 5, hence, the posthypnotic suggestion improved inhibition by affecting resolve implementation.

SATH suggests that posthypnotic suggestions enhance performance as they provide an environment for hypnotized participants to mentally practice a suggested strategy. The new trigger-response contingency, however, does not become automatic (Tobis & Kihlstrom, 2010). Therefore, posthypnotic suggestions result in newly learned trigger-response contingencies that are semi-automatic responses. These semi-automatic responses can be implemented more efficiently compared to when new trigger-responses are not practiced at all. Hence, in Studies 4 and 5, posthypnotic suggestions enhanced the implementation of suppression and resolve, respectively, and did not create automatic responses. Interestingly, improved resolve or suppression implementation both required increased recruitment of proactive control.

Accordingly, our findings indicate that cognitive control exertion, regardless of being in the form of suppression or resolve, requires an immediate mental effort. Considering the argument of Ainslie (2020) that resolve is the effortless component of the inhibition, it seems that his statement does not delineate between "*changing*" and "*changed*" preferences. Ainslie (2020) discussed that in situations where delayed gratification is required (Mischel et al., 1989), individuals have two choices, either using suppression or resolve. For instance, when choosing between unhealthy/satisfying or healthy/unsatisfying food, one can effortfully suppress the urge to pick the unhealthy/appealing food. Alternatively, one can effortlessly choose the healthy/insipid if the preferences for unsatisfying food items would be changed. In the same sense suppressing the irrelevant response in the Stroop task can also become effortless. If participants practice the task to the degree that the task-relevant response becomes automatic, then suppressing task-irrelevant response can be effortless (Dulaney & Rogers, 1994; MacLeod, 1991; Protopapas et al., 2014). In other words, implementing resolve must be distinguished from relying on habits, that is, automatic trigger-response contingencies. Consequently, resolve, like suppressing, depends on expenditure of mental effort since an automatic response must be stopped, and limited cognitive resources should be employed to form a new trigger-response (motivational) contingency (Botvinick & Braver, 2015; Shenhav et al., 2017). The main difference between resolve and suppression is what kind of novel trigger-response contingencies are created. In resolve implementation, new trigger-response contingencies are related to associating a stimulus with negative or positive consequences; on the other hand, during suppression, trigger-response contingencies are proactively blocking distracting information. In conclusion, no matter resolve or suppression, inhibition implementation requires immediate mental effort, which results in mental fatigue (Hockey, 2011; Shenhav et al., 2017).

3.5. Implications, Limitations, and Future Perspectives

As the current project is concerned with the application of posthypnotic suggestions in cognitive neuroscience, it is appropriate to discuss an implication of the current results for future utilizations of task-relevant posthypnotic suggestions in experimental investigations. It is common practice to use standardized hypnotic-suggestibility tests to categorize participants as low- and high-hypnotic-suggestibles and then, for curbing the effects of confounding variables, low- and high-hypnotic-suggestibles are compared (Iani et al., 2009; Iani et al., 2006; Raz et al., 2006; Raz et al., 2003). This design effectively employs the participants of the former group as controls for the latter (Cox & Bryant, 2008; Wagstaff, 1996). A group of participants can only be utilized as controls if participants in the control and experimental conditions are identical in every possible aspect except for one measurable property. When this assumption is not met, no conclusion can be drawn from differences between the control and the experimental groups. The results of Study 3 indicate that the variance in hypnotic-suggestibility scores originates from two sources, that is, differences in suggestibility and hypnotizability. Based on the SATH proposition, variance in suggestibility is caused by individual differences in the employment of several top-down processes, including cognitive-simulation, sensory-adaptation, and mental practice/problem-solving. On the other hand, differences in hypnotizability can be related to various psychosocial variables, including willingness and openness (Green & Lynn, 2011; Lynn, Laurence, et al., 2015), the prior expectations about hypnosis (Kirsch & Lynn, 1997; Terhune et al., 2017), expectations induced by the wordings of suggestions (Lynn, Neufeld, & Matyi, 1987; Matthews, Bennett, Bean, & Gallagher, 1985; Spanos, 1971), rapport with the hypnotist (Lynn et al., 2019), and motivation to respond to suggestions (Jones & Spanos, 1982). Low-hypnotic-suggestible participants, therefore, are distinguishable from high-hypnotic-suggestibles due to differences in cognitive factors, psychosocial factors, or a combination of both. In line with Study 3, many other studies had also shown the HGSHS and similar hypnotic-suggestibility scales are not homogenous (e.g., McConkey et al., 1980; Oakman & Woody, 1996; Piesbergen & Peter, 2006). This fact underscores our concerns that hypnotic-suggestibility scores are not suitable for predicting participants' responses to a random experimental suggestion.

Therefore, in line with other researchers (e.g., Acunzo & Terhune, 2021; Jensen et al., 2017), our findings suggest that utilization of low-hypnotic-suggestibles as the only constituents of control groups may be misleading. A better approach, which has been discussed by Jensen et al. (2017), is to utilize medium- and low-hypnotic-suggestible participants in both the control and experimental groups to increase the generalizability of findings. Responding to this call, in Study 5, both medium- and high-hypnotic-suggestibles have been included in the sample. The results showed they were indistinguishable, both at the behavioral and neural level, with regard to responsiveness to our posthypnotic suggestion. In line with our results, several clinical (e.g., Alladin & Alibhai, 2007; Golden, 2012; Schoenberger, 2000) and experimental studies (e.g., Perri, Rossani, & Di Russo, 2019) found that hypnotic-suggestibility scores were a poor predictor of participants' responsiveness to a given experimental suggestion.

The first limitation in the current project was related to the fact that I focused on two functions, inhibition and updating. This focus resulted in the absence of a task measuring the shifting function in the current project. As discussed in the introduction, most taxonomies of executive functions consist of three functions, including shifting besides inhibition and updating (Diamond, 2013; Miyake et al., 2000). Noteworthy, before using posthypnotic suggestions for examining neurocognitive correlates of different executive functions, it was necessary to elucidate how they affect performance in cognitive tasks. Consequently, I needed to focus (1) on the updating function, as, in contrast to inhibition and shifting, it can only be enhanced by alterations in top-down processes, and (2) the inhibition function, as many studies had shown that posthypnotic suggestions could improve it (Lifshitz et al., 2013). However, in future studies, it is vital to investigate whether task-relevant posthypnotic suggestions can also affect shifting tasks and, if so, elucidate the neurocognitive correlates of these enhancements.

The second limitation of the current project is related to the low-spatial resolution of EEG and ERP. Even though ERPs have a high temporal resolution, however, due to the inverse problem issue, no firm conclusion can be made about the sources of observed ERP components (Luck, 2014). The information about the sources of components could enable us to scrutinize engaged neural circuits more precisely. In the current project, however, I used ERPs to compensate for the low-temporal resolution of fMRI and similar techniques (Amaro & Barker, 2006; Constable, 2006), which was more critical than having a high spatial resolution for addressing my questions. It is interesting to use multimodal neuroimaging data in future studies, as it can have a high temporal and spatial resolution simultaneously (Uludag & Roebroeck, 2014).

4. Conclusion

In conclusion, by focusing on updating in working memory, a pure top-down component of executive functions, we showed that the effects of task-relevant posthypnotic suggestions on performance can indeed be attributed to alterations in top-down and not bottom-up processes. Based on this finding, we proposed a new hypnosis theory that, besides other critical hypnotic phenomena, can explain the effects of task-relevant posthypnotic suggestions. The simulation-adaption theory of hypnosis (SATH), which was empirically tested by modeling hypnotic-suggestibility scores with CFA and SEM, suggests that three fundamental top-down cognitive processes are employed by willing and cooperative participants for responding to suggestions offered by the hypnotist. These top-down processes are cognitive-simulation (i.e., imagination), sensory-adaptation (i.e., top-down downregulation of sensory input), and mental practice (i.e., practicing a novel strategy in a mentally simulated environment). After elucidating the driving mechanism of task-relevant posthypnotic suggestions, they have been utilized for addressing several long-lasting questions concerning the structure and nature of executive functions. In summary: (a) the psychometric and ERP results pointed to both unity and diversity of executive functions. Inhibition and updating rely on both function-specific early-stage processing and a shared attentional system, whose activation triggers the frontocentral P3 ERP component. (b) Even though both the manual and vocal versions of the Stroop task measure suppression, the vocal version is more taxing. Specifically, the vocal task version engages a response-production-related locus of interference, which is absent in the manual version and cannot be affected by posthypnotic suggestions. (c) Both subcomponents of the inhibition function, that is, suppression and resolve, are implemented effortfully. Together, the current project not only contributed to understanding hypnosis and suggestions but presented successful examples of how task-relevant posthypnotic suggestions can be employed to address long-lasting questions in cognitive neuroscience.

References

Abrahamse, E. L., & Verwey, W. B. (2008). Context dependent learning in the serial RT task. *Psychological Research, 72*(4), 397-404. doi:10.1007/s00426-007-0123-5

Acunzo, D., & Terhune, D. (2021). A critical review of standardized measures of hypnotic suggestibility. *International Journal of Clinical and Experimental Hypnosis*.

Ainslie, G. (2020). Willpower With and Without Effort. *Behavioral and Brain Sciences*, 1-81. doi:10.1017/S0140525X20000357

Alladin, A., & Alibhai, A. (2007). Cognitive hypnotherapy for depression: an empirical investigation. *International Journal of Clinical and Experimental Hypnosis, 55*(2), 147-166. doi:10.1080/00207140601177897

Alvarez, J. A., & Emory, E. (2006). Executive function and the frontal lobes: a meta-analytic review. *Neuropsychology Review, 16*(1), 17-42. doi:10.1007/s11065-006-9002-x

Amaro, E., Jr., & Barker, G. J. (2006). Study design in fMRI: basic principles. *Brain and Cognition, 60*(3), 220-232. doi:10.1016/j.bandc.2005.11.009

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes1. In *Psychology of learning and motivation* (Vol. 2, pp. 89-195): Elsevier.

Augustinova, M., & Ferrand, L. (2012). Suggestion does not de-automatize word reading: evidence from the semantically based Stroop task. *Psychonmic Bulletin and Review, 19*(3), 521-527. doi:10.3758/s13423-012-0217-y

Augustinova, M., Parris, B. A., & Ferrand, L. (2019). The Loci of Stroop Interference and Facilitation Effects With Manual and Vocal Responses. *Frontiers in Psychology, 10*, 1786. doi:10.3389/fpsyg.2019.01786

Baddeley, A. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology, 49*(1), 5-28.

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience, 4*(10), 829-839. doi:10.1038/nrn1201

Baddeley, A., & Hitch, G. (1974). Working Memory. *8*, 47-89. doi:10.1016/s0079-7421(08)60452-1

Badzakova-Trajkov, G., Barnett, K. J., Waldie, K. E., & Kirk, I. J. (2009). An ERP investigation of the Stroop task: the role of the cingulate in attentional allocation and conflict resolution. *Brain Research, 1253*, 139-148. doi:10.1016/j.brainres.2008.11.069

Banich, M. T. (2019). The Stroop Effect Occurs at Multiple Points Along a Cascade of Control: Evidence From Cognitive Neuroscience Approaches. *Frontiers in Psychology, 10*. doi:10.3389/fpsyg.2019.02164

Best, J. R., Miller, P. H., & Jones, L. L. (2009). Executive Functions after Age 5: Changes and Correlates. *Developmental Review, 29*(3), 180-200. doi:10.1016/j.dr.2009.05.002

Blakemore, S. J., Oakley, D. A., & Frith, C. D. (2003). Delusions of alien control in the normal brain. *Neuropsychologia, 41*(8), 1058-1067. doi:10.1016/s0028-3932(02)00313-5

Bongartz, W. (1985). German norms for the Harvard Group Scale of Hypnotic Susceptibility, Form A. *International Journal of Clinical and Experimental Hypnosis, 33*(2), 131-139. doi:10.1080/00207148508406643

Botvinick, M., & Braver, T. (2015). Motivation and cognitive control: from behavior to neural mechanism. *Annual Review of Psychology, 66*, 83-113. doi:10.1146/annurev-psych-010814-015044

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624-652. doi:10.1037/0033-295X.108.3.624

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. *Trends in Cognitive Sciences, 8*(12), 539-546. doi:10.1016/j.tics.2004.10.003

Braffman, W., & Kirsch, I. (1999). Imaginative suggestibility and hypnotizability: an empirical analysis. *Journal of Personality and Social Psychology, 77*(3), 578-587. doi:10.1037//0022-3514.77.3.578

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends in Cognitive Sciences, 16*(2), 106-113. doi:10.1016/j.tics.2011.12.010

Braver, T. S., Paxton, J. L., Locke, H. S., & Barch, D. M. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. *Proceedings of the National Academy of Sciences of the United States of America, 106*(18), 7351-7356. doi:10.1073/pnas.0808187106

Brouwer, A. M., Hogervorst, M. A., van Erp, J. B., Heffelaar, T., Zimmerman, P. H., & Oostenveld, R. (2012). Estimating workload using EEG spectral power and ERPs in the n-back task. *J Neural Eng, 9*(4), 045008. doi:10.1088/1741-2560/9/4/045008

Brown, R. J., & Oakley, D. A. (2004). An integrative cognitive theory of hypnosis and high hypnotizability. *The highly hypnotizable person: Theoretical, experimental and clinical issues*, 152-186.

Campbell, N. A., Reece, J. B., Urry, L. A., Cain, M. L., Wasserman, S. A., Minorsky, P. V., & Jackson, R. B. (2018). *Biology: a global approach*: Pearson New York, NY.

Clark, M. A., Springmann, M., Hill, J., & Tilman, D. (2019). Multiple health and environmental impacts of foods. *Proceedings of the National Academy of Sciences of the United States of America*. doi:10.1073/pnas.1906908116

Coderre, E., Conklin, K., & van Heuven, W. J. (2011). Electrophysiological measures of conflict detection and resolution in the Stroop task. *Brain Research, 1413*, 51-59. doi:10.1016/j.brainres.2011.07.017

Coderre, E., & van Heuven, W. J. (2014). Electrophysiological explorations of the bilingual advantage: evidence from a Stroop task. *PloS One, 9*(7), e103424. doi:10.1371/journal.pone.0103424

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychological Review, 97*(3), 332-361. doi:10.1037/0033-295X.97.3.332

Collette, F., Van der Linden, M., Laureys, S., Delfiore, G., Degueldre, C., Luxen, A., & Salmon, E. (2005). Exploring the unity and diversity of the neural substrates of executive functioning. *Human Brain Mapping, 25*(4), 409-423. doi:10.1002/hbm.20118

Constable, R. T. (2006). Challenges in fMRI and Its Limitations. In S. H. Faro & F. B. Mohamed (Eds.), *Functional MRI: Basic Principles and Clinical Applications* (pp. 75-98). New York, NY: Springer New York.

Cooper, R., & Shallice, T. (2000). Contention scheduling and the control of routine activities. *Cognitive Neuropsychology, 17*(4), 297-338. doi:10.1080/026432900380427

Coulacoglou, C., & Saklofske, D. H. (2017). Advances in Latent Variable Measurement Modeling. In *Psychometrics and Psychological Assessment* (pp. 67-88).

Cox, R. E., & Bryant, R. A. (2008). Advances in hypnosis research: methods, designs and contributions of intrinsic and instrumental hypnosis. *The Oxford handbook of hypnosis: Theory, research, and practice, 2008*, 311-336.

Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychology Review, 93*(3), 283-321.

Dhooge, E., & Hartsuiker, R. J. (2010). The distractor frequency effect in picture-word interference: Evidence for response exclusion. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*(4), 878-891. doi:10.1037/a0019128

Dhooge, E., & Hartsuiker, R. J. (2011). The distractor frequency effect in a delayed picture-word interference task: further evidence for a late locus of distractor exclusion. *Psychon Bull Rev, 18*(1), 116-122. doi:10.3758/s13423-010-0026-0

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135-168. doi:10.1146/annurev-psych-113011-143750

Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental Cognitive Neuroscience, 18*, 34-48. doi:10.1016/j.dcn.2015.11.005

Donchin, E., & Coles, M. G. H. (1988). Is the P300 component a manifestation of context updating? *Behavioral and Brain Sciences, 11*(03), 357. doi:10.1017/s0140525x00058027

Dong, S., Reder, L. M., Yao, Y., Liu, Y., & Chen, F. (2015). Individual differences in working memory capacity are reflected in different ERP and EEG patterns to task difficulty. *Brain Research, 1616*, 146-156. doi:10.1016/j.brainres.2015.05.003

Dulaney, C. L., & Rogers, W. A. (1994). Mechanisms underlying reduction in Stroop interference with practice for young and old adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20*(2), 470-484. doi:10.1037//0278-7393.20.2.470

Dunn, B. R., Dunn, D. A., Languis, M., & Andrews, D. (1998). The relation of ERP components to complex memory processing. *Brain and Cognition, 36*(3), 355-376.

Eden, G. F., VanMeter, J. W., Rumsey, J. M., Maisog, J. M., Woods, R. P., & Zeffiro, T. A. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature, 382*(6586), 66-69. doi:10.1038/382066a0

Egner, T., Jamieson, G., & Gruzelier, J. (2005). Hypnosis decouples cognitive control from conflict monitoring processes of the frontal lobe. *Neuroimage, 27*(4), 969-978. doi:10.1016/j.neuroimage.2005.05.002

Egner, T., & Raz, A. (2007). Cognitive control processes and hypnosis. *Hypnosis and conscious states: The cognitive neuroscience perspective*, 29-50.

Eid, M., Geiser, C., Koch, T., & Heene, M. (2017). Anomalous results in G-factor models: Explanations and alternatives. *Psychological Methods, 22*(3), 541-562. doi:10.1037/met0000083

Eid, M., Krumm, S., Koch, T., & Schulze, J. (2018). Bifactor Models for Predicting Criteria by General and Specific Factors: Problems of Nonidentifiability and Alternative Solutions. *J Intell, 6*(3). doi:10.3390/jintelligence6030042

Elkins, G. R., Barabasz, A. F., Council, J. R., & Spiegel, D. (2015). Advancing research and practice: The revised APA Division 30 definition of hypnosis. *American Journal of Clinical Hypnosis, 57*(4), 378-385. doi:10.1080/00029157.2015.1011465

Enriquez-Geppert, S., Konrad, C., Pantev, C., & Huster, R. J. (2010). Conflict and inhibition differentially affect the N200/P300 complex in a combined go/nogo and stop-signal task. *Neuroimage, 51*(2), 877-887. doi:10.1016/j.neuroimage.2010.02.043

Evans, J. L., Selinger, C., & Pollak, S. D. (2011). P300 as a measure of processing capacity in auditory and visual domains in specific language impairment. *Brain Research, 1389*, 93-102. doi:10.1016/j.brainres.2011.02.010

Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: a review. *Psychophysiology, 45*(1), 152-170. doi:10.1111/j.1469-8986.2007.00602.x

Fonken, Y. M., Kam, J. W. Y., & Knight, R. T. (2020). A differential role for human hippocampus in novelty and contextual processing: Implications for P300. *Psychophysiology, 57*(7), e13400. doi:10.1111/psyp.13400

Frank, T. D. (2016). Perception adapts via top-down regulation to task repetition: A Lotka-Volterra-Haken modeling analysis of experimental data. *Journal of Integrative Neuroscience, 15*(1), 67-79. doi:10.1142/S0219635216500059

Gajewski, P. D., & Falkenstein, M. (2013). Effects of task complexity on ERP components in Go/Nogo tasks. *International Journal of Psychophysiology, 87*(3), 273-278. doi:10.1016/j.ijpsycho.2012.08.007

Gazzaniga, M. S. (2000). *The new cognitive neurosciences*: MIT press.

Geng, J., Schnur, T. T., & Janssen, N. (2013). Relative speed of processing affects interference in Stroop and picture–word interference paradigms: evidence from the distractor frequency effect. *Language, Cognition and Neuroscience, 29*(9), 1100-1114. doi:10.1080/01690965.2013.846473

Gobel, E. W., Parrish, T. B., & Reber, P. J. (2011). Neural correlates of skill acquisition: decreased cortical activity during a serial interception sequence learning task. *Neuroimage, 58*(4), 1150-1157. doi:10.1016/j.neuroimage.2011.06.090

Golden, W. L. (2012). Cognitive hypnotherapy for anxiety disorders. *American Journal of Clinical Hypnosis, 54*(4), 263-274. doi:10.1080/00029157.2011.650333

Goldman-Rakic, P. S. (1991). Chapter 16 Cellular and circuit basis of working memory in prefrontal cortex of nonhuman primates. In *The Prefrontal Its Structure, Function and Cortex Pathology* (pp. 325-336).

Goldman-Rakic, P. S. (1995). Cellular basis of working memory. *Neuron, 14*(3), 477-485. doi:10.1016/0896-6273(95)90304-6

Green, J. P., & Lynn, S. J. (2011). Hypnotic responsiveness: expectancy, attitudes, fantasy proneness, absorption, and gender. *International Journal of Clinical and Experimental Hypnosis, 59*(1), 103-121. doi:10.1080/00207144.2011.522914

Hammond, D. C. (1990). *Handbook of hypnotic suggestions and metaphors*: WW Norton & Company.

Hammond, D. C. (1998). *Hypnotic induction and suggestion*. Chicago, IL: American Society of Clinical Hypnosis.

Han, L., Liu, Y., Zhang, D., Jin, Y., & Luo, Y. (2013). Low-arousal speech noise improves performance in N-back task: an ERP study. *PloS One, 8*(10), e76261. doi:10.1371/journal.pone.0076261

Hanslmayr, S., Pastotter, B., Bauml, K. H., Gruber, S., Wimber, M., & Klimesch, W. (2008). The electrophysiological dynamics of interference during the Stroop task. *Journal of Cognitive Neuroscience, 20*(2), 215-225. doi:10.1162/jocn.2008.20020

Harrington, D. (2009). *Confirmatory factor analysis*: Oxford university press.

Hesslow, G. (2002). Conscious thought as simulation of behaviour and perception. *Trends in Cognitive Sciences, 6*(6), 242-247. doi:10.1016/s1364-6613(02)01913-7

Hickey, C., Chelazzi, L., & Theeuwes, J. (2010). Reward Changes Salience in Human Vision via the Anterior Cingulate. *Journal of Neuroscience, 30*(33), 11096-11103. doi:10.1523/jneurosci.1026-10.2010

Hockey, G. R. J. (2011). A motivational control theory of cognitive fatigue. In *Cognitive fatigue: Multidisciplinary perspectives on current research and future applications.* (pp. 167-187).

Iani, C., Ricci, F., Baroni, G., & Rubichi, S. (2009). Attention control and susceptibility to hypnosis. *Consciousness and Cognition, 18*(4), 856-863. doi:10.1016/j.concog.2009.07.002

Iani, C., Ricci, F., Gherri, E., & Rubichi, S. (2006). Hypnotic suggestion modulates cognitive conflict: the case of the flanker compatibility effect. *Psychological Science, 17*(8), 721-727. doi:10.1111/j.1467-9280.2006.01772.x

Indefrey, P. (2011). The spatial and temporal signatures of word production components: a critical update. *Frontiers in Psychology, 2*, 255. doi:10.3389/fpsyg.2011.00255

Indefrey, P., & Levelt, W. J. (2004). The spatial and temporal signatures of word production components. *Cognition, 92*(1-2), 101-144. doi:10.1016/j.cognition.2002.06.001

Jamieson, G. A., & Woody, E. (2007). Dissociated control as a paradigm for cognitive neuroscience research and theorizing in hypnosis. *Hypnosis and conscious states: The cognitive neuroscience perspective*, 111-129.

Jensen, M. P., Adachi, T., Tome-Pires, C., Lee, J., Osman, Z. J., & Miro, J. (2015). Mechanisms of hypnosis: toward the development of a biopsychosocial model. *International Journal of Clinical and Experimental Hypnosis, 63*(1), 34-75. doi:10.1080/00207144.2014.961875

Jensen, M. P., Jamieson, G. A., Lutz, A., Mazzoni, G., McGeown, W. J., Santarcangelo, E. L., . . . Terhune, D. B. (2017). New directions in hypnosis research: strategies for advancing the cognitive and clinical neuroscience of hypnosis. *Neurosci Conscious, 3*(1). doi:10.1093/nc/nix004

Jones, B., & Spanos, N. P. (1982). Suggestions for altered auditory sensitivity, the negative subject effect and hypnotic susceptibility: A signal detection analysis. *Journal of Personality and Social Psychology, 43*(3), 637-647. doi:10.1037/0022-3514.43.3.637

Karr, J. E., Areshenkoff, C. N., Rast, P., Hofer, S. M., Iverson, G. L., & Garcia-Barrera, M. A. (2018). The unity and diversity of executive functions: A systematic review and re-analysis of latent variable studies. *Psychological Bulletin, 144*(11), 1147-1185. doi:10.1037/bul0000160

Kihlstrom, J. F. (1985). Hypnosis. *Annual Review of Psychology, 36*, 385-418. doi:10.1146/annurev.ps.36.020185.002125

Kihlstrom, J. F. (2008). The domain of hypnosis, revisited. *The Oxford handbook of hypnosis: Theory, research and practice*, 21-52.

Kindt, M., Bierman, D., & Brosschot, J. F. (1996). Stroop versus Stroop: Comparison of a card format and a single-trial format of the standard color-word Stroop task and the emotional Stroop task. *Personality and Individual Differences, 21*(5), 653-661. doi:10.1016/0191-8869(96)00133-x

Kirsch, I. (1996). Hypnotic enhancement of cognitive-behavioral weight loss treatments—Another meta-reanalysis. *Journal of Consulting and Clinical Psychology, 64*(3), 517-519. doi:10.1037/0022-006x.64.3.517

Kirsch, I. (1997). Suggestibility or hypnosis: what do our scales really measure? *International Journal of Clinical and Experimental Hypnosis, 45*(3), 212-225. doi:10.1080/00207149708416124

Kirsch, I. (1999). Hypnosis and placebos: response expectancy as a mediator of suggestion effects. *Anales de Psicología*.

Kirsch, I., & Lynn, S. J. (1997). Hypnotic involuntariness and the automaticity of everyday life. *American Journal of Clinical Hypnosis, 40*(1), 329-348. doi:10.1080/00029157.1997.10403402

Landry, M., Da Silva Castanheira, J., Sackur, J., & Raz, A. (2021). Difficult Turned Easy: Suggestion Renders a Challenging Visual Task Simple. *Psychological Science, 32*(1), 39-49. doi:10.1177/0956797620954856

Landry, M., Lifshitz, M., & Raz, A. (2017). Brain correlates of hypnosis: A systematic review and meta-analytic exploration. *Neuroscience and Biobehavioral Reviews, 81*(Pt A), 75-98. doi:10.1016/j.neubiorev.2017.02.020

Levelt, W. J., Roelofs, A., & Meyer, A. S. (1999). Multiple perspectives on word production. *Behavioral and Brain Sciences, 22*(1), 61-69. doi:10.1017/s0140525x99451775

Lifshitz, M., Aubert Bonn, N., Fischer, A., Kashem, I. F., & Raz, A. (2013). Using suggestion to modulate automatic processes: from Stroop to McGurk and beyond. *Cortex, 49*(2), 463-473. doi:10.1016/j.cortex.2012.08.007

Lindelov, J. K., Overgaard, R., & Overgaard, M. (2017). Improving working memory performance in brain-injured patients using hypnotic suggestion. *Brain, 140*(4), 1100-1106. doi:10.1093/brain/awx001

Liotti, M., Woldorff, M. G., Perez, R., & Mayberg, H. S. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia, 38*(5), 701-711.

Liu, T., Xiao, T., & Shi, J. (2017). Neural Correlates of Response Inhibition and Conflict Control on Facial Expressions. *Frontiers in Human Neuroscience, 11*, 657. doi:10.3389/fnhum.2017.00657

Lobier, M. A., Peyrin, C., Pichat, C., Le Bas, J. F., & Valdois, S. (2014). Visual processing of multiple elements in the dyslexic brain: evidence for a superior parietal dysfunction. *Frontiers in Human Neuroscience, 8*, 479. doi:10.3389/fnhum.2014.00479

Lopresti-Goodman, S. M., Turvey, M. T., & Frank, T. D. (2013). Negative hysteresis in the behavioral dynamics of the affordance "graspable". *Atten Percept Psychophys, 75*(5), 1075-1091. doi:10.3758/s13414-013-0437-x

Luck, S. J. (2014). *An introduction to the event-related potential technique*: MIT press.

Ludwig, V. U., Stelzel, C., Krutiak, H., Magrabi, A., Steimke, R., Paschke, L. M., . . . Walter, H. (2014). The suggestible brain: posthypnotic effects on value-based decision-making. *Social Cognitive and Affective Neuroscience, 9*(9), 1281-1288. doi:10.1093/scan/nst110

Lush, P., Botan, V., Scott, R. B., Seth, A. K., Ward, J., & Dienes, Z. (2020). Trait phenomenological control predicts experience of mirror synaesthesia and the rubber hand illusion. *Nat Commun, 11*(1), 4853. doi:10.1038/s41467-020-18591-6

Lynn, S. J., & Green, J. P. (2011). The sociocognitive and dissociation theories of hypnosis: toward a rapprochement. *International Journal of Clinical and Experimental Hypnosis, 59*(3), 277-293. doi:10.1080/00207144.2011.570652

Lynn, S. J., Green, J. P., Kirsch, I., Capafons, A., Lilienfeld, S. O., Laurence, J. R., & Montgomery, G. H. (2015). Grounding Hypnosis in Science: The "New" APA Division

30 Definition of Hypnosis as a Step Backward. *American Journal of Clinical Hypnosis, 57*(4), 390-401. doi:10.1080/00029157.2015.1011472

Lynn, S. J., Green, J. P., Polizzi, C. P., Ellenberg, S., Gautam, A., & Aksen, D. (2019). Hypnosis, hypnotic phenomena, and hypnotic responsiveness: Clinical and Research Foundations-A 40-Year Perspective. *International Journal of Clinical and Experimental Hypnosis, 67*(4), 475-511. doi:10.1080/00207144.2019.1649541

Lynn, S. J., Laurence, J. R., & Kirsch, I. (2015). Hypnosis, suggestion, and suggestibility: an integrative model. *American Journal of Clinical Hypnosis, 57*(3), 314-329. doi:10.1080/00029157.2014.976783

Lynn, S. J., Nash, M. R., Rhue, J. W., Frauman, D. C., & Sweeney, C. A. (1984). Nonvolition, expectancies, and hypnotic rapport. *Journal of Abnormal Psychology, 93*(3), 295-303. doi:10.1037/0021-843x.93.3.295

Lynn, S. J., Neufeld, V., & Matyi, C. L. (1987). Inductions versus suggestions: Effects of direct and indirect wording on hypnotic responding and experience. *Journal of Abnormal Psychology, 96*(1), 76-79. doi:10.1037/0021-843x.96.1.76

Lynn, S. J., Rhue, J. W., & Weekes, J. R. (1990). Hypnotic involuntariness: A social cognitive analysis. *Psychological Review, 97*(2), 169-184. doi:10.1037/0033-295x.97.2.169

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: an integrative review. *Psychological Bulletin, 109*(2), 163-203. doi:10.1037/0033-2909.109.2.163

Mahon, B. Z., Costa, A., Peterson, R., Vargas, K. A., & Caramazza, A. (2007). Lexical selection is not by competition: a reinterpretation of semantic interference and facilitation effects in the picture-word interference paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(3), 503-535. doi:10.1037/0278-7393.33.3.503

Matthews, W. J., Bennett, H., Bean, W., & Gallagher, M. (1985). Indirect versus direct hypnotic suggestions--an initial investigation: a brief communication. *International Journal of Clinical and Experimental Hypnosis, 33*(3), 219-223. doi:10.1080/00207148508406650

Mazzoni, G., Rotriquenz, E., Carvalho, C., Vannucci, M., Roberts, K., & Kirsch, I. (2009). Suggested visual hallucinations in and out of hypnosis. *Consciousness and Cognition, 18*(2), 494-499. doi:10.1016/j.concog.2009.02.002

McConkey, K. M., Sheehan, P. W., & Law, H. G. (1980). Structural analysis of the Harvard Group Scale of Hypnotic Susceptibility, Form A. *International Journal of Clinical and Experimental Hypnosis, 28*(2), 164-175. doi:10.1080/00207148008409838

McGeown, W. J., Venneri, A., Kirsch, I., Nocetti, L., Roberts, K., Foan, L., & Mazzoni, G. (2012). Suggested visual hallucination without hypnosis enhances activity in visual areas of the brain. *Consciousness and Cognition, 21*(1), 100-116. doi:10.1016/j.concog.2011.10.015

Milburn, M. C. (2010). Cognitive-Behavior Therapy and Change: Unconditional Self Acceptance and Hypnosis in CBT. *Journal of Rational-Emotive and Cognitive-Behavior Therapy, 29*(3), 177-191. doi:10.1007/s10942-010-0121-1

Milling, L. S., Gover, M. C., & Moriarty, C. L. (2018). The effectiveness of hypnosis as an intervention for obesity: A meta-analytic review. *Psychology of Consciousness: Theory, Research, and Practice, 5*(1), 29-45. doi:10.1037/cns0000139

Mischel, W., Shoda, Y., & Rodriguez, M. I. (1989). Delay of gratification in children. *Science, 244*(4907), 933-938. doi:10.1126/science.2658056

Miyake, A., & Friedman, N. P. (2012). The Nature and Organization of Individual Differences in Executive Functions: Four General Conclusions. *Current Directions in Psychological Science, 21*(1), 8-14. doi:10.1177/0963721411429458

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cognitive Psychology, 41*(1), 49-100. doi:10.1006/cogp.1999.0734

Nakao, Y., Kodabashi, A., Yarita, M., Fujimoto, T., & Tamura, T. (2012). *Temporal activities during P3 components on the working memory-related brain regions: N-back ERP study.* Paper presented at the Proceedings of 2012 IEEE-EMBS International Conference on Biomedical and Health Informatics.

Niendam, T. A., Laird, A. R., Ray, K. L., Dean, Y. M., Glahn, D. C., & Carter, C. S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cognitive, Affective & Behavioral Neuroscience, 12*(2), 241-268. doi:10.3758/s13415-011-0083-5

Norman, D. A., & Shallice, T. (1986). Attention to Action. In *Consciousness and Self-Regulation* (pp. 1-18).

Oakman, J. M., & Woody, E. Z. (1996). A taxometric analysis of hypnotic susceptibility. *Journal of Personality and Social Psychology, 71*(5), 980-991. doi:10.1037/0022-3514.71.5.980

Ouyang, G., Sommer, W., Zhou, C., Aristei, S., Pinkpank, T., & Abdel Rahman, R. (2016). Articulation artifacts during overt language production in event-related brain potentials: Description and correction. *Brain Topography, 29*(6), 791-813. doi:10.1007/s10548-016-0515-1

Palfi, B., Parris, B. A., McLatchie, N., Kekecs, Z., & Dienes, Z. (2020). Can unconscious intentions be more effective than conscious intentions? Test of the role of metacognition in hypnotic response. *Cortex*. doi:10.1016/j.cortex.2020.11.006

Parris, B. A., & Dienes, Z. (2013). Hypnotic suggestibility predicts the magnitude of the imaginative word blindness suggestion effect in a non-hypnotic context. *Consciousness and Cognition, 22*(3), 868-874. doi:10.1016/j.concog.2013.05.009

Parris, B. A., Dienes, Z., & Hodgson, T. L. (2012). Temporal constraints of the word blindness posthypnotic suggestion on Stroop task performance. *Journal of Experimental Psychology: Human Perception and Performance, 38*(4), 833-837. doi:10.1037/a0028131

Parris, B. A., Dienes, Z., & Hodgson, T. L. (2013). Application of the ex-Gaussian function to the effect of the word blindness suggestion on Stroop task performance suggests no word blindness. *Frontiers in Psychology, 4*, 647. doi:10.3389/fpsyg.2013.00647

Parris, B. A., Hasshim, N., & Dienes, Z. (2021). Look into my eyes: Pupillometry reveals that a post-hypnotic suggestion for word blindness reduces Stroop interference by marshalling greater effortful control. *European Journal of Neuroscience*. doi:10.1111/ejn.15105

Parris, B. A., Sharma, D., Weekes, B. S. H., Momenian, M., Augustinova, M., & Ferrand, L. (2019). Response Modality and the Stroop Task. *Experimental Psychology, 66*(5), 361-367. doi:10.1027/1618-3169/a000459

Perri, R. L., Rossani, F., & Di Russo, F. (2019). Neuroelectric evidences of top-down hypnotic modulation associated with somatosensory processing of sensory and limbic regions. *Neuroimage, 202*, 116104. doi:10.1016/j.neuroimage.2019.116104

Piesbergen, C., & Peter, B. (2006). An investigation of the factor structure of the Harvard Group Scale of Hypnotic Susceptibility, Form A (HGSHS:A). *Contemporary Hypnosis, 23*(2), 59-71. doi:10.1002/ch.311

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology, 118*(10), 2128-2148. doi:10.1016/j.clinph.2007.04.019

Popper, K. R. (1971). CONJECTURAL KNOWLEDGE: MY SOLUTION OF THE PROBLEM OF INDUCTION. *Revue Internationale De Philosophie, 25(95/96 (1/2))*, 167-197.

Protopapas, A., Vlahou, E. L., Moirou, D., & Ziaka, L. (2014). Word reading practice reduces Stroop interference in children. *Acta Psychologica, 148*, 204-208. doi:10.1016/j.actpsy.2014.02.006

Raz, A. (2005). Attention and hypnosis: neural substrates and genetic associations of two converging processes. *International Journal of Clinical and Experimental Hypnosis, 53*(3), 237-258. doi:10.1080/00207140590961295

Raz, A., Fan, J., & Posner, M. I. (2005). Hypnotic suggestion reduces conflict in the human brain. *Proceedings of the National Academy of Sciences of the United States of America, 102*(28), 9978-9983. doi:10.1073/pnas.0503064102

Raz, A., Kirsch, I., Pollard, J., & Nitkin-Kaner, Y. (2006). Suggestion reduces the stroop effect. *Psychological Science, 17*(2), 91-95. doi:10.1111/j.1467-9280.2006.01669.x

Raz, A., Landzberg, K. S., Schweizer, H. R., Zephrani, Z. R., Shapiro, T., Fan, J., & Posner, M. I. (2003). Posthypnotic suggestion and the modulation of Stroop interference under cycloplegia. *Consciousness and Cognition, 12*(3), 332-346. doi:10.1016/s1053-8100(03)00024-2

Raz, A., & Shapiro, T. (2002). Hypnosis and neuroscience: a cross talk between clinical and cognitive research. *Archives of General Psychiatry, 59*(1), 85-90. doi:10.1001/archpsyc.59.1.85

Redding, G. M., & Gerjets, D. A. (1977). Stroop effect: interference and facilitation with verbal and manual responses. *Perceptual and Motor Skills, 45*(1), 11-17. doi:10.2466/pms.1977.45.1.11

Reise, S. P. (2012). The rediscovery of bifactor measurement models. *Multivariate behavioral research, 47*(5), 667-696.

Rottschy, C., Langner, R., Dogan, I., Reetz, K., Laird, A. R., Schulz, J. B., . . . Eickhoff, S. B. (2012). Modelling neural correlates of working memory: a coordinate-based meta-analysis. *Neuroimage, 60*(1), 830-846. doi:10.1016/j.neuroimage.2011.11.050

Rugg, M. D., & Curran, T. (2007). Event-related potentials and recognition memory. *Trends in Cognitive Sciences, 11*(6), 251-257. doi:10.1016/j.tics.2007.04.004

Ruitenberg, M. F., De Kleine, E., Van der Lubbe, R. H., Verwey, W. B., & Abrahamse, E. L. (2012). Context-dependent motor skill and the role of practice. *Psychological Research, 76*(6), 812-820. doi:10.1007/s00426-011-0388-6

Schacht, A., Adler, N., Chen, P., Guo, T., & Sommer, W. (2012). Association with positive outcome induces early effects in event-related brain potentials. *Biological Psychology, 89*(1), 130-136. doi:10.1016/j.biopsycho.2011.10.001

Scharinger, C., Soutschek, A., Schubert, T., & Gerjets, P. (2017). Comparison of the working memory load in n-back and working memory span tasks by means of eeg frequency band power and p300 amplitude. *Frontiers in Human Neuroscience, 11*, 6. doi:10.3389/fnhum.2017.00006

Schmiedek, F., Hildebrandt, A., Lovden, M., Wilhelm, O., & Lindenberger, U. (2009). Complex span versus updating tasks of working memory: the gap is not that deep. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*(4), 1089-1096. doi:10.1037/a0015730

Schoenberger, N. E. (2000). Research on hypnosis as an adjunct to cognitive-behavioral psychotherapy. *International Journal of Clinical and Experimental Hypnosis, 48*(2), 154-169. doi:10.1080/00207140008410046

Sharma, D., & McKenna, F. P. (1998). Differential components of the manual and vocal Stroop tasks. *Memory and Cognition, 26*(5), 1033-1040. doi:Doi 10.3758/Bf03201181

Sheehan, P. W., Donovan, P., & MacLeod, C. M. (1988). Strategy manipulation and the Stroop effect in hypnosis. *Journal of Abnormal Psychology, 97*(4), 455-460. doi:10.1037/0021-843x.97.4.455

Shenhav, A., Musslick, S., Lieder, F., Kool, W., Griffiths, T. L., Cohen, J. D., & Botvinick, M. M. (2017). Toward a Rational and Mechanistic Account of Mental Effort. *Annual Review of Neuroscience, 40*, 99-124. doi:10.1146/annurev-neuro-072116-031526

Shitova, N., Roelofs, A., Schriefers, H., Bastiaansen, M., & Schoffelen, J. M. (2016). Using brain potentials to functionally localise Stroop-like effects in colour and picture naming: Perceptual encoding versus word planning. *PloS One, 11*(9), e0161052. doi:10.1371/journal.pone.0161052

Shitova, N., Roelofs, A., Schriefers, H., Bastiaansen, M., & Schoffelen, J. M. (2017). Control adjustments in speaking: Electrophysiology of the Gratton effect in picture naming. *Cortex, 92*, 289-303. doi:10.1016/j.cortex.2017.04.017

Shor, R. E., & Orne, E. C. (1962). *Harvard group scale of hypnotic susceptibility*: Consulting Psychologists Press.

Shor, R. E., & Orne, E. C. (1963). Norms on the Harvard group scale of hypnotic susceptibility, form A. *International Journal of Clinical and Experimental Hypnosis, 11*, 39-47. doi:10.1080/00207146308409226

Smolker, H. R., Friedman, N. P., Hewitt, J. K., & Banich, M. T. (2018). Neuroanatomical Correlates of the Unity and Diversity Model of Executive Function in Young Adults. *Frontiers in Human Neuroscience, 12*, 283. doi:10.3389/fnhum.2018.00283

Spanos, N. P. (1971). Goal-directed fantasy and the performance of hypnotic test suggestions. *Psychiatry, 34*(1), 86-96. doi:10.1080/00332747.1971.11023658

Spanos, N. P., Cobb, P. C., & Gorassini, D. R. (1985). Failing to resist hypnotic test suggestions: a strategy for self-presenting as deeply hypnotized. *Psychiatry, 48*(3), 282-292. doi:10.1080/00332747.1985.11024288

Starreveld, P. A., & La Heij, W. (2017). Picture-word interference is a Stroop effect: A theoretical analysis and new empirical findings. *Psychon Bull Rev, 24*(3), 721-733. doi:10.3758/s13423-016-1167-6

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643.

Terhune, D. B., Cleeremans, A., Raz, A., & Lynn, S. J. (2017). Hypnosis and top-down regulation of consciousness. *Neuroscience and Biobehavioral Reviews, 81*(Pt A), 59-74. doi:10.1016/j.neubiorev.2017.02.002

Tobis, I. P., & Kihlstrom, J. F. (2010). Allocation of attentional resources in posthypnotic suggestion. *International Journal of Clinical and Experimental Hypnosis, 58*(4), 367-382. doi:10.1080/00207144.2010.499330

Uludag, K., & Roebroeck, A. (2014). General overview on the merits of multimodal neuroimaging data fusion. *Neuroimage, 102 Pt 1*, 3-10. doi:10.1016/j.neuroimage.2014.05.018

van der Graaf, F. H., Maguire, R. P., Leenders, K. L., & de Jong, B. M. (2006). Cerebral activation related to implicit sequence learning in a Double Serial Reaction Time task. *Brain Research, 1081*(1), 179-190. doi:10.1016/j.brainres.2006.01.103

van Maanen, L., van Rijn, H., & Borst, J. P. (2009). Stroop and picture-word interference are two sides of the same coin. *Psychon Bull Rev, 16*(6), 987-999. doi:10.3758/PBR.16.6.987

Wager, T. D., & Smith, E. E. (2003). Neuroimaging studies of working memory: a meta-analysis. *Cognitive, Affective & Behavioral Neuroscience, 3*(4), 255-274. doi:10.3758/cabn.3.4.255

Wagstaff, G. F. (1996). Methodological issues in hypnosis. *Psychological research: Innovative methods and strategies*, 202-220.

Watter, S., Geffen, G. M., & Geffen, L. B. (2001). The n-back as a dual-task: P300 morphology under divided attention. *Psychophysiology, 38*(6), 998-1003.

West, R., & Alain, C. (1999). Event-related neural activity associated with the Stroop task. *Brain Research: Cognitive Brain Research, 8*(2), 157-164.

Wilding, E. L., & Ranganath, C. (2011). Electrophysiological Correlates of Episodic Memory Processes. *The Oxford handbook of ERP components*, 373-396.

Williams, J. M., Mathews, A., & MacLeod, C. (1996). The emotional Stroop task and psychopathology. *Psychological Bulletin, 120*(1), 3-24. doi:10.1037/0033-2909.120.1.3

Woody, E. Z., & Barnier, A. J. (2008). Hypnosis scales for the twenty-first century: What do we need and how should we use them. *The Oxford handbook of hypnosis: Theory, research, and practice*, 255-282.

Woody, E. Z., & Bowers, K. S. (1994). *A frontal assault on dissociated control*: Guilford Press New York.

Yang, S., Luo, W., Zhu, X., Broster, L. S., Chen, T., Li, J., & Luo, Y. (2014). Emotional content modulates response inhibition and perceptual processing. *Psychophysiology, 51*(11), 1139-1146. doi:10.1111/psyp.12255

Yuan, J., Xu, S., Yang, J., Liu, Q., Chen, A., Zhu, L., . . . Li, H. (2011). Pleasant mood intensifies brain processing of cognitive control: ERP correlates. *Biological Psychology, 87*(1), 17-24. doi:10.1016/j.biopsycho.2011.01.004

Yuan, P., & Raz, N. (2014). Prefrontal cortex and executive functions in healthy adults: a meta-analysis of structural neuroimaging studies. *Neuroscience and Biobehavioral Reviews, 42*, 180-192. doi:10.1016/j.neubiorev.2014.02.005

Zahedi, A., Abdel Rahman, R., Sturmer, B., & Sommer, W. (2019). Common and specific loci of Stroop effects in vocal and manual tasks, revealed by event-related brain potentials and posthypnotic suggestions. *Journal of Experimental Psychology: General, 148*(9), 1575-1594. doi:10.1037/xge0000574

Zahedi, A., Luczak, A., & Sommer, W. (2020). Modification of food preferences by posthypnotic suggestions: An event-related brain potential study. *Appetite, 151*, 104713. doi:10.1016/j.appet.2020.104713

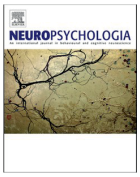
Zahedi, A., Stuermer, B., Hatami, J., Rostami, R., & Sommer, W. (2017). Eliminating stroop effects with post-hypnotic instructions: Brain mechanisms inferred from EEG. *Neuropsychologia, 96*, 70-77. doi:10.1016/j.neuropsychologia.2017.01.006

Zahedi, A., Sturmer, B., & Sommer, W. (2020). Can posthypnotic suggestions boost updating in working memory? Behavioral and ERP evidence. *Neuropsychologia, 148*, 107632. doi:10.1016/j.neuropsychologia.2020.107632

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: http://www.elsevier.com/locate/neuropsychologia



Can posthypnotic suggestions boost updating in working memory? Behavioral and ERP evidence

Anoushiravan Zahedi [a,*], Birgit Stürmer [b], Werner Sommer [a]

[a] Department of Psychology, Humboldt-Universität zu Berlin, Rudower Chaussee 18, 12489, Berlin, Germany
[b] International Psychoanalytic University Berlin, Stromstraße 1, 10555 Berlin, Germany

A R T I C L E I N F O

Keywords:
Working memory (WM)
Updating
Posthypnotic suggestions
Event-related potentials (ERP)
Mental practice

A B S T R A C T

Updating is an essential executive function (EF), responsible for storing, retrieving, and substituting information in working memory (WM). Here we investigated whether posthypnotic suggestions (PHS) given to high-hypnotizable participants can enhance updating in WM and measured neural correlates of the observed effects by recording event-related brain potentials (ERP). In a tone-monitoring task different syllables were presented in random order, requiring a response to every fourth presentation of a given syllable. Experiment 1 ($n = 19$) established the relationship between performance and several ERP components across updating load (different numbers of syllables). In Experiment 2 ($n = 18$), a no-hypnosis (NH) and a hypnosis-plus-PHS session were administrated in counterbalanced order. Task instructions, presented at the beginning of the sessions, emphasized a cognitive strategy, demanding imagination of visual counters, a strategy that was also emphasized during PHS. PHS additionally contained suggestions stimulating cognitive simulation of the task, where participants were advised to apply the suggested strategy. Relative to the NH session, PHS enhanced WM performance with medium to large effect sizes. In ERPs, PHS increased the P2 and P3 components, indicating the proactive recruitment of control-related attention and updating-related cognitive control processes, respectively. PHS also reduced updating load effects in the posterior recognition component, suggesting diminished demands on WM buffers. These ERP findings suggest that PHS enhanced updating in WM by strengthening proactive control, which may have diminished the necessity for reactive control. Hence, the present results suggest that our PHS had worked like mental practice helping participants to develop an efficient and context-dependent trigger-action contingency. Consequentially, the present study provides a new framework for employing PHSs, which may be used as a basis for developing new training regimes for modifying WM or other EFs.

1. Introduction

Executive functions (EFs) support appropriate actions in novel situations when the existing behavioral repertoire is inadequate (Baddeley, 2003; Diamond, 2013; Miyake et al., 2000). In all proposed taxonomies (Diamond, 2013; Miyake et al., 2000), three EFs are considered to be pivotal; (1) updating: storing, retrieving and substituting information in working memory (WM) buffers, (2) inhibition: suppressing prepotent but task-inappropriate actions, and (3) shifting: redistributing attentional resources between sub-tasks. Updating serves a central function in cognition and general intelligence (Wilhelm et al., 2013) and, consequently, there have been many attempts to improve this function, for example, via cognitive training. However, results have been mixed. Some meta-analyses of training studies (Melby-Lervag and Hulme, 2016; Melby-Lervag et al., 2016) indicated little evidence for improvements in WM (Diamond and Ling, 2016; Melby-Lervag et al., 2016). If present, enhancements were limited, only achieved through very extensive training, and confined to the trained cognitive skill (Diamond and Ling, 2016; Melby-Lervag et al., 2016). An exception may be intense cognitive training in children, where transfer was reported along with neural changes (Klingberg, 2010; Moreno et al., 2011; Rueda et al., 2005; Thorell et al., 2009). In the present study, we assessed a novel approach to enhance updating in WM by applying posthypnotic suggestions (PHS).

Even though PHSs can enhance performance in various cognitive tasks, such as Stroop (e.g., Parris et al., 2012; Raz et al., 2005; Raz et al., 2006; Zahedi et al., 2019; Zahedi et al., 2017), Eriksen (Iani et al., 2006), Simon (Iani et al., 2009), and Go-NoGo tasks (Zahedi et al., 2020), the

* Corresponding author. Institut für Psychologie, Rudower Chaussee 18, 12489, Berlin, Germany.
E-mail address: zahedian@hu-berlin.de (A. Zahedi).

https://doi.org/10.1016/j.neuropsychologia.2020.107632
Received 17 February 2020; Received in revised form 5 September 2020; Accepted 15 September 2020
Available online 23 September 2020

underlying mechanisms of these enhancements are not well known. To our knowledge, most published experimental studies applying PHSs have focused on tasks capitalizing on the inhibition function (for review please see Lifshitz et al., 2013). Such tasks require a novel response, for which participants need to refrain from a habitual, prepotent response. For instance, in the classic Stroop task, color words are written in different ink colors, while participants must respond to the ink colors and ignore the word meanings. The immediate implementation of the required response – attending to ink colors but ignoring word meanings – is hard to achieve for most participants. That means, in most cases, participants still read the words, as evidenced in the Stroop effect, that is, longer reaction times when word meanings and ink colors are incongruent rather than congruent (MacLeod, 1991). PHSs, on the other hand, can efficiently enhance performance in Stroop and other tasks requiring inhibition; for instance, in Stroop tasks, PHSs have been shown to decrease or eliminate the Stroop effect (Raz, 2005; Raz and Shapiro, 2002; Zahedi et al., 2017, 2019). Importantly, PHSs are usually elaborated versions of standard task instructions or repetitions of important elements thereof. For instance, a common PHS used for Stroop tasks is: "You will not be able to read the words presented on the monitor, and they will seem to you like words from a foreign language", which is very similar to the standard instruction: "do not read the words and only respond to the ink colors". As PHSs do not introduce new strategies, how can they enhance performance in these tasks?

To answer this question, it is necessary to consider the nature of hypnosis. There are two traditional perspectives on hypnosis. First, the state approach conceives hypnosis as an "altered" state of consciousness or, more specifically, a state of consciousness, characterized by concentration on oneself, dissociation from the surroundings, and increased suggestibility (Elkins et al., 2015). Based on this definition, the state of consciousness during hypnosis differs from the waking state similar to meditation or mindfulness or in a unique way that is exclusive to hypnosis (Elkins et al., 2015). A second perspective on hypnosis focuses on sociocognitive aspects (Green and Lynn, 2011; Jensen et al., 2017; Kihlstrom, 1985; Lynn and Green, 2011; Lynn et al., 2015, 2019). That is, hypnosis is defined as the process "in which one person, designated the subject, responds to suggestions offered by another person, designated the hypnotist, for experiences involving alterations in perception, memory, and voluntary action" (Kihlstrom, 1985, p. 385). Partially in line with these definitions, there are two accounts how hypnotic and posthypnotic suggestions can affect behavior. (1) Effects of PHSs might be attributed to cognitive control mechanisms being decoupled from cognitive monitoring (Egner et al., 2005; Egner and Raz, 2007). As a consequence, "the internal generation and implementation of strategic performance adjustments", that is, EFs, are effectively inactivated and instead, participants become more "amenable to carrying out externally suggested task strategies" and run "in a more automatic manner akin to a contention scheduling system" (Egner and Raz, 2007, p. 34–35). This account is closely related to the state definition, since the decoupling of cognitive control from monitoring processes is quite different from the normal state of consciousness. (2) Alternatively, effects of PHSs can be related to enhanced utilization of top-down regulation (Parris, 2017; Terhune et al., 2017), that is, by using EFs that fully rely on preceding monitoring processes. This account, using the assumptions of the sociocognitive definition, attributes effects of PHSs to the enhanced utilization of top-down processes.

The decoupling account was primarily devised to explain observations that during or after hypnosis alone without task-relevant suggestions, performance may be worse than in no-hypnosis conditions (NH) (e.g., Sheehan et al., 1988). For instance, Egner et al. (2005) observed that after hypnosis-alone, despite increased activity in the anterior cingulate cortex (ACC), reflecting an increase in conflict monitoring, performance was unaffected, which was interpreted as a sign that monitoring processes were decoupled from cognitive control. However, the increased ACC activity after hypnosis-alone might also be related to increased autonomic arousal due to positive mood (Rudebeck et al., 2014), which was induced by comfort-related, task-irrelevant hypnotic suggestions included in the hypnosis script of Egner et al. (2005). Nonetheless, Egner and Raz (2007) attempted to reconcile the decoupling account with observations that task-related PHSs can enhance performance in different cognitive tasks (e.g., Iani et al., 2006; Raz et al., 2006; Raz et al., 2003). They argued that effects of PHSs are caused by the enhanced capability to follow an externally presented strategy while the capability to internally generate and implement behavioral adjustments is interrupted.

Two points must be discussed about the suggestion of Egner and Raz (2007). First, they suggested that under influence of PHSs participants can better follow externally presented strategies "due to the fact that task-processing is unencumbered by signals from internal performance monitoring" (p. 35). However, being unencumbered by monitoring signals does not answer how innate conflicts in inhibition tasks, for instance, the conflict between word meanings and ink colors in Stroop tasks, can be resolved more efficiently. Second, they suggested that effects of PHSs can be similar to "contention scheduling". In essence, contention scheduling holds that there is an intermediate domain of action, between reflexive schemata, which cannot be controlled at all, and scripts that are flexibly controlled by EFs (Cooper and Shallice, 2000). According to contention scheduling, in any situation, the sets of potential "source schemata" compete with each other in "the determination of their activation value"; the schema, which first exceeds a given threshold, will be selected (Norman and Shallice, 1986). However, when doing a Stroop task for the first time, participants have only one schema, namely, the reflexive response of word reading. So how can PHSs cause a second schema (color detection) to be developed and dominate? Do participants learn a new response? If so, learning a new response is the paragon of using top-down regulation, which has been shown consistently to depend on the activation and coordination of cognitive control and cognitive monitoring (e.g., Gobel et al., 2011; van der Graaf et al., 2006), which Egner and Raz (2007) suggested to be disrupted during hypnosis (i.e., when receiving PHSs). Further, even in the presence of two source schemata, contention scheduling still requires inhibition of the irrelevant response to ensure activation of the correct schema (Cooper and Shallice, 2000). In other words, according to the principles of contention scheduling, without any top-down control the stronger schema (word reading) will be selected. For the weaker but task-relevant schema (color detection) to be selected, cognitive control is required. Summarizing, it seems, Egner and Raz (2007) assume that hypnosis decouples cognitive control from monitoring processes and PHSs activate the proper schema (color detection); however, they do not explain how this is done. Further, they do not discuss the fate of the prepotent and automatic schema (word reading).

Therefore, the decoupling account appears to attribute improvements in performance to alterations in bottom-up processes. In other words, if internal cognitive control and cognitive monitoring processes are decoupled, and consequentially, EFs are impaired (i.e., there is no internal generation and implementation of performance adjustments), task-inappropriate but automatic responses cannot be held in check by top-down regulation. Then, how can task inappropriate but automatic responses become ineffective? The only possible manner to make an automatic response ineffective without top-down regulation is by disrupting bottom-up processes. For instance, if PHSs in Stroop tasks made participants temporarily dyslexic – dyslexia is the difficulty in reading in individuals who otherwise possess the cognitive functioning and education required for fluent reading and has been related to the disruption of activities in occipito-temporal visual cortices (Eden et al., 1996; Lobier et al., 2014) – the weaker schema (color detection) could be selected without utilizing top-down regulation. In contrast to the decoupling/bottom-up account, the enhanced utilization of top-down processes implies that PHSs cause (1) learning new responses and making them semi-automatic, so they can compete with automatic, task-irrelevant responses, and (2) faster detection of conflicts and enhanced deployment of inhibition to suppress irrelevant schemata.

Hence, for relevant schemata to be selected more efficiently, it is required that cognitive monitoring processes to be in close contact with cognitive control. Although the decoupling/bottom-up and top-down accounts seem contradictory, the literature is inconclusive. For instance, Parris (2017) concluded that the role of EFs in hypnosis is non-identified, and Terhune et al. (2017) could not rule out the decoupling account.

The reason is, with regard to inhibition tasks, the observed effects of PHSs can be explained by both accounts. (1) PHS effects may be based on alterations in bottom-up processes, for instance, blocking interfering sensory input to prevent conflicts during the information processing stage; for instance, in the case of Stroop tasks, blocking semantic input. To understand the bottom-up account in Stroop tasks one may consider a special form of dyslexia, characterized by letter-by-letter reading, which is caused by damage to the occipito-temporal region of the left hemisphere through which visual word-forms are attained (Warrington and Shallice, 1980). In the same manner, if PHSs in Stroop tasks can affect bottom-up processes, for instance, by decoupling or impairing the letter recognition or word-form system, task performance will be enhanced without employing cognitive control. Alternatively, (2) the imagery techniques involved in PHSs may facilitate mental practice, which helps participants implement the strategy presented in standard task instructions more efficiently. In other words, participants may deploy enhanced top-down cognitive control to detect and suppress interfering information more efficiently, which in turn facilitates conflict resolution. That means, in Stroop tasks, even though participants still can read words, they will detect conflicts faster and inhibit word meanings earlier and more efficiently and, therefore, show decreased Stroop effects. It is important to notice that top-down control can affect bottom-up processes as early as thalamic activities (e.g., Frank, 2016; Manita et al., 2015; Saalmann and Kastner, 2009).

The existing evidence, therefore, is insufficient to distinguish between the decoupling/bottom-up and top-down accounts of PHS effects. For example, Raz et al. (2005) reported that PHSs decrease conflicts in brain (ACC). Now, was the conflict diminished because bottom-up processes blocked word recognition or because participants used superior top-down control to detect conflicts and suppress the irrelevant information early on? Furthermore, in most Stroop tasks, using PHSs, participants showed some Stroop effects, even though smaller in comparison to NH conditions, indicating that participants were still able to read words (e.g., Augustinova and Ferrand, 2012; Zahedi et al., 2019). Again, both accounts can explain this observation. Whether under the influence of PHSs, participants' ability to read words is partially impaired, that is, if they become temporarily dyslexic, or alternatively, they exert enhanced cognitive control and inhibit word meanings more efficiently, Stroop effects would be decreased but not necessarily eliminated.

Existing neurocognitive findings can also be explained by both of the decoupling/bottom-up and top-down accounts. For instance, PHS in a Stroop task study (Zahedi et al., 2019) affected early event-related brain potential (ERP) components such as N1 and N2, which can be interpreted as supporting the bottom-up account (e.g., Hillyard and Anllo-Vento, 1998). However, these early components could have been affected also by proactive control, that is, a preemptive form of control recruited in advance of a situation that potentially requires cognitive control, and contrasts with reactive control that would only be recruited after the necessity of control is detected (Braver, 2012; Braver et al., 2009). Hence, the N1 and N2 components could have been affected by additional top-down processes suppressing irrelevant information (e.g., Abdel Rahman and Sommer, 2008). Further, PHS-induced performance enhancement in Stroop tasks was related with increased frontal EEG activity in the theta and beta frequency ranges (Zahedi et al., 2017), possibly indicating enhanced utilization of EFs (Reinhart and Nguyen, 2019). However, on a different account, one could also argue that the increase in frontal theta and beta activities was related to diminished demands on cognitive control. For example, Huster et al. (2013) suggested that frontal beta activity may reflect an active process that promotes the maintenance of the current motor set. With respect to the effects of PHSs in Stroop tasks, it can then be suggested that increased beta activity represents a continuation of unencumbered rhythmic behavior. Also, increased frontal theta activity may be related to an altered state of mind (Huster et al., 2013) rather than the enhanced utilization of cognitive control.

The same argument can be used for other inhibition tasks as well. Consequently, we think inhibition tasks are inappropriate to address the underlying mechanisms of PHS effects. In contrast to inhibition or selective attention (another EF closely related to inhibition), the updating function cannot be notably improved by blocking sensory input. Updating might be enhanced through the deployment of additional top-down regulation but blocking of any information that is task-relevant could only diminish memory performance. More specifically, in updating tasks, different pieces of information are consecutively presented and all of them have to be encoded and processed for solving the task. These pieces of information are needed only for a short time, after which they become irrelevant and must be substituted by more recent information. Updating tasks require different responses depending on highly variable conditions; therefore, reflexive response schemata alone (highly inflexible lower-level schemata, which cannot be controlled or adapted) cannot enhance performance. Therefore, if PHSs can enhance performance in updating tasks, it will strongly argue in favor of enhanced top-down regulation deployed or enabled by PHSs.

It might be argued that also in updating tasks, bottom up processes might contribute to improving performance, for example, by attenuating distracting, irrelevant stimuli. Although this may be a plausible scenario in highly noisy environments, it is less likely in controlled laboratory situations where irrelevant stimuli are largely absent. Further, even if changes in bottom-up processes would enhance task performance, the ERP components related to the updating function, such as components related to the activities of WM buffers, will be unaffected, since even with blockage of irrelevant stimuli, the same number of task-relevant stimuli must still be processed. This is in contrast to inhibition tasks, where alterations in ERP data cannot distinguish between changes in bottom-up processes or top-down regulation, since both can equivocally affect early perception-related and late conflict-related ERP components. Therefore, in the present study, we applied PHS in an updating task by considering PHSs to be an efficient means to boost mental imagery helping participants to learn and implement a cognitive strategy. Importantly, in order to separate the effects of PHSs from mnemonic strategies in general, the same strategy was suggested to the participants in conditions with and without PHS and they were advised to strictly adhere to this strategy and not to use any other.

In the following, we will use the terms "PHS", "task-instruction", and "strategy" to refer to three different concepts. "PHS" exclusively refers to suggestions delivered during hypnosis; "task-instructions" (sometimes simply "instructions") relates to the explanations of the task requirements given at the beginning of the task; and finally, "strategy" refers to the visual strategy suggested in both, the task instructions as well as in PHS. The visual strategy explicitly asked participants to imagine a 4-digit number, where each digit relates to one of the four different syllables presented in the task and, further, to update (increase) this number at each new presentation of the corresponding syllable.

Lindelov et al. (2017) have shown that PHS can enhance WM performance. However, several points weaken the relevance of this study for the present aims. First, participants were patients with brain injuries, limiting the generalizability of the results to the normal population. Second, no neural data were recorded, which is essential for testing many of our hypotheses regarding effects of PHSs. Third, for measuring WM, Lindelov et al. (2017) used the working memory index from the Wechsler adult intelligence scale, which has been questioned as an appropriate measure of WM as conceptualized by current theoretical models (Hill et al., 2010). Finally, they did not separate the effects of suggestions and cognitive strategies, as their PHS was related to age-regression and plasticity, which could be implemented with different strategies.

We also aimed at elucidating the neurocognitive mechanisms of updating and its modulation by PHSs. Neurocognitive studies of updating in WM have mainly used either span tasks, which obviously are not pure measures of updating as they involve shifting (Scharinger et al., 2017), or n-back tasks (e.g., Brouwer et al., 2012; Dong et al., 2015; Evans et al., 2011; Nakao et al., 2012; Scharinger et al., 2017; Watter et al., 2001). N-back tasks have also been disputed as a pure measure of updating, as they might require also other EFs (Miyake et al., 2000; Schmiedek et al., 2009).

Before generalizing ERP results from n-back tasks to the updating function, they should be cross-validated by another task measuring updating (Scharinger et al., 2017), in order to rule out task-specificity, and conclude function-specificity. An appropriate task for this aim, taxing the updating function, appears to be the tone-monitoring task (Miyake et al., 2000). In this task, a limited number of auditory stimuli (e.g., syllables or tones) are presented repeatedly in random order. Participants count how often each stimulus is presented and every time one of the counts reaches a certain number, that particular count has to be restarted, indicated by a corresponding button press. Therefore, the tone-monitoring task requires to *store* several pieces of information (the individual counts), *retrieve* the count of the currently presented stimulus, and *substitute* the old number in memory with the new one.

Summarizing, in two experiments we studied, first, the updating function in WM and its neurocognitive mechanisms using the tone-monitoring task with syllable stimuli and, second, explored PHSs as a tool for enhancing updating in WM and, third, tried to elucidate the underlying neurocognitive correlates of PHS effects by recording multichannel ERPs.

2. Experiment 1

The aim of this experiment was to establish load effects and their ERP correlates in the tone monitoring task. Based on findings from n-back and other memory tasks, we expected several ERP components to be sensitive to updating load. ERP components in updating tasks can be classified into three categories. First, the ERP components, which are related to the perception of stimuli and stimulus properties, such as N1 and N2; second, the ERP components, which are related to the incorporation of attentional resources and EFs, such as P2 and P3; and third, ERP components related to storing, retrieving and substituting information in short-term memory buffers, such as the posterior old-new component.

N1 amplitude decreases with more distributed attention, that is, when perceiving more diverse stimuli, the N1 component decreases (e.g., Frtusova et al., 2013; Han et al., 2013). P2 amplitude is sensitive to the level of attention (e.g., Han et al., 2013) and correlates positively with performance in recall (Dunn et al., 1998) and auditory feedback tasks (Li et al., 2015). Amplitude of the posterior N2 component increases with lower stimulus predictability (Folstein and Van Petten, 2008); this is relevant for tone-monitoring because the relative frequency of each syllable decreases as load increases. In n-back tasks, P3 amplitude decreases with increasing load (e.g., Dong et al., 2015; Evans et al., 2011; Frtusova et al., 2013; Nakao et al., 2012; Scharinger et al., 2017; Watter et al., 2001) and should do so also in the tone-monitoring task. In other words, the P3 component, which is related to the engagement of EFs (Polich, 2007), should decrease when updating load increases as the efficiency of updating is reduced under higher load (Diamond, 2013).

Finally, we also considered two ERP components, which are usually studied in recognition memory tasks. When items are classified into previously encountered (old) or novel, a negative frontal component is larger in response to new relative to old items but is insensitive to the confidence of choice. The frontal old/new component has therefore been related to familiarity-based recognition. In contrast, a positive posterior component observed in the same task is larger to correctly identified old items that have been studied deeply rather than superficially (Rugg and Curran, 2007). Therefore, the posterior old/new component has been related to recollection. Even though the tone-monitoring task is not a recognition task, we consider both components to be relevant because, firstly, they are present in many n-back tasks (e.g., Scharinger et al., 2017) and, second, recognition is an integral part of the updating function, suggesting the posterior recollection component to be involved in updating. Further, as the posterior recollection component has been correlated with the number of objects held in WM (Vogel and Machizawa, 2004), it should be of relevance for the tone-monitoring task and the updating function.

2.1. Method

2.1.1. Participants

The sample for Experiment 1 consisted of 19 individuals (11 women; $M = 27.6\,years;\ range = 20-44,\ SD = 5.9$). Participation was compensated either with course credits or 8 € per hour. The study had been approved by the ethics committee of the department of Psychology at the Humboldt-Universität zu Berlin and written informed consent was obtained from the participants.

The sample size of Experiment 1 ($n = 19$) was based on a power analysis with expected effect sizes (Cohen's $f = .50$ equivalent to $\eta_p^2 = .20$) derived from n-back tasks (e.g., Brouwer et al., 2012; Dong et al., 2015; Evans et al., 2011; Nakao et al., 2012; Scharinger et al., 2017; Watter et al., 2001); the estimated power (Faul et al., 2007; Kreidler et al., 2013) for both RTs and ERPs was above recommended values, $1 - \beta > 0.90$ (Cohen, 1988, 2016).

2.1.2. Stimuli, task, and procedure

A variant of the tone-monitoring task with up to four different syllables per block,/ba/,/be/,/bu/and/bi/, was employed. The syllables, spoken by a woman, were recorded and edited to a uniform duration of 500 ms. Each trial consisted of a fixation cross presented for 500 ms, followed by a syllable for 500 ms. Simultaneously with the syllable, a white square (2.5 by 2.5 cm, visual angle ± 1.5°) was presented on the screen for 2 s, followed by the next trial. The background color of the monitor was grey (RGB 100, 100, 100). An assignment table of buttons to syllables was always present on the monitor but participants were encouraged to memorize the assignments in order to minimize eye movements.

Each experimental block contained 25 trials, consisting of two, three or four different syllables, that is, imposing updating Load 2, 3, or 4. For example, in a Load 3 block, the syllables /ba/, /be/, and /bu/ were presented in random order until a total of 25 trials had been reached. Before each block, the corresponding number and types of syllables were indicated. Ten blocks for each of the three different load conditions were conducted, yielding 30 blocks in total. Participants were instructed to count each syllable separately; after the fourth presentation, they should press a button assigned to this syllable and reset their corresponding mental count to zero. Each block contained six trials requiring a button press and count reset. The order of syllables within blocks and the order of blocks were pseudo-randomized, allowing the consecutive presentations of at most (1) three identical syllables within a block and (2) two blocks of the same load. At the beginning of the task, two blocks with Load 2 were used for practice.

During task completion, participants sat approximately 70 cm away from the monitor. The sound intensity of syllables was uniformly set to 75–78 dB; syllables were presented via a speaker located in the mid-sagittal plane behind the monitor. The task was conducted in a sound-attenuated, electrically shielded experimental chamber. One session took approximately 2 h.

Performance was measured in terms of reaction times (RTs) and accuracy per load condition and participant. RTs were defined as the interval between syllable onset and button press and calculated only for correct button presses. Accuracy was measured as percentage of correct responses (hits plus correct rejections).

2.1.3. EEG recordings and ERP analyses

EEG was recorded from 46 Ag/AgCl electrodes, mounted in an elastic cap (Easy Cap, FMS GmbH, München, Germany), according to the international 10–20 system. The vertical and horizontal electrooculograms were measured with four additional electrodes, two below each eye and two at the outer canthi. An electrode, placed at the left mastoid, served as common reference. Recordings were conducted with Brain Amps DC amplifiers (Brain Products GmbH, München, Germany), at a sampling rate of 1000 Hz without any additional filters. Impedances of all electrodes were kept below 10 kΩ. Triggers for stimuli and responses were inserted online into EEG data by synchronization between Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) and BrainVision Recorder (Brain Products GmbH, München, Germany).

Offline, EEG signals were recalculated to average reference. For correcting eye movement artifacts, prototypical horizontal and vertical eye movements and blinks, recorded at the end of the experiment, were fed into BESA 6.0 software, to produce rectifier matrices. Eye movements and blinks were corrected in continuous EEG data with the linear derivation method (Berg and Scherg, 1991; Hoechstetter et al., 2004). Data were band-pass filtered at 0.05–40 Hz and visually inspected for remaining artifacts; these intervals were excluded from further analyses. Data were segmented, averaged, and analyzed with EEGLAB (Delorme and Makeig, 2004). All segments with non-correctable artifacts were excluded, resulting in a loss of less than 10% of all trials. Averaging was done per electrode and load condition (including all presentations of a corresponding syllable). However, since amplitudes at the different electrodes in each ROI were averaged, electrode locations were not considered as a factor in the ANOVAs.

2.1.4. Regions of interests for ERP analyses

For analyzing the N1 component a fronto-parietal ROI (FC1, FCz, FC2, C3, Cz, C4, CP3, CPz, CP4, P1, Pz and P2 electrodes) was used, which is in-line with Frtusova et al. (2013). Analysis of P2 took place within a centro-frontal ROI (FC1, FCz, FC2, C3, Cz, C4, CP3, CPz, and CP4 electrodes) in line with Dunn et al. (1998) and Han et al. (2013). In line with Folstein and Van Petten (2008), analysis of the posterior N2 component occurred at a centro-parietal ROI (CP3, CPz, CP4, P5, P1, Pz, P2, P6, PO7, POz, and PO8 electrodes). Finally, in line with several studies (Dong et al., 2015; Evans et al., 2011; Han et al., 2013; Polich, 2007; Scharinger et al., 2017; Watter et al., 2001) the P3 component was analyzed, at electrodes within a parieto-central ROI, that is, C3, Cz, C4, CP3, CPz, CP4, P1, Pz, and P2.

Finally, we measured the old/new complex, consisting of anterior and posterior components. For the anterior component, we used a frontal ROI with electrodes AF3, AF4, F3, Fz, F4, FC1, FCz, and FC2. Because the topography of the posterior aspect of the old/new component was left-lateralized (Fig. 3), which is in line with several studies (Rugg and Curran, 2007; Rugg and Yonelinas, 2003; Wilding and Ranganath, 2011), we chose an asymmetrical parietal ROI with electrodes P5, P1, Pz, P2, PO7, POz, O1, and Oz.

Neural sources were assessed with low-resolution brain electromagnetic tomography (LORETA-KEY software package). Importantly, LORETA-Key software does not require an a priori assumption of the number or location of dipoles, as it assumes distributed sources rather than equivalent dipoles.

2.1.5. Statistical analyses

For statistical analyses of performance and EEG data, analyses of variance (ANOVA) was used, with repeated measures on the factor task load (Load 2, 3, and 4). Whenever the assumption of sphericity was violated, the Huynh-Feldt correction was used and Huynh-Feldt epsilon with corrected p-values were reported. For unplanned post-hoc analyses, Bonferroni correction in behavioral data and Tukey-Kramer (HSD) in ERP data were applied, and corrected *p*-values are reported.

2.2. Results and discussion

2.2.1. Performance

Experiment 1 measured performance and ERP correlates of updating load (the number of syllables to be monitored). As can be seen in Fig. 1, mean RTs increased and accuracy decreased with higher load. ANOVA showed the main effect of load in mean RTs, $F(2, 36) = 62.17$, $p < .001$, $\varepsilon = .81$, $\eta_p^2 = .77$, which monotonically increased across load levels ($Load\ 2 < Load\ 3 < Load\ 4$; $p_{Load\ 2-3} < .001$ ($\eta_p^2 = .81$), $p_{Load\ 2-4} < .001$ ($\eta_p^2 = .81$), $p_{Load\ 3-4} = .006$ ($\eta_p^2 = .42$)), and in mean accuracy, $F(2, 36) = 37.81$, $p < .001$, $\eta_p^2 = .67$, which decreased with load ($Load\ 2 > Load\ 3 = Load\ 4$; $p_{Load\ 2-3} < .001$ ($\eta_p^2 = .72$), $p_{Load\ 2-4} < .001$ ($\eta_p^2 = .73$), $p_{Load\ 3-4} = .126$ ($\eta_p^2 = .21$)).

Hence, the tone-monitoring task is sensitive to updating load and, therefore, measures the updating function.

2.2.2. Event-related brain potentials

Figs. 2 and 3 show grand average ERP waveforms and topographies of the targeted ERP components. ANOVA of N1 amplitude (Fig. 2a) between 80 and 180 ms revealed a main effect of load, $F(2, 36) = 4.9$, $p = .014$, $\eta_p^2 = .21$. Post-hoc contrasts showed N1 amplitude to diminish with increasing load: $Load\ 2 > Load\ 3 = Load\ 4$ ($M = -0.53, -0.36$, *vs.* $-0.31\ \mu V$; $p_{Load\ 2-3} = .033$ ($\eta_p^2 = .29$), $p_{Load\ 2-4} = .049$ ($\eta_p^2 = .26$), $p_{Load\ 3-4} = .856$ ($\eta_p^2 = .01$)). Hence, as expected, when participants attended to more diverse stimuli with increasing load, N1 amplitude diminished.

For the P2 component at 165–215 ms (Fig. 2b), ANOVA revealed a main effect of updating load, $F(2, 36) = 4.7$, $p = .014$, $\varepsilon = .79$, $\eta_p^2 = .21$. Post-hoc contrasts revealed that P2 was larger for Load 4 than Load 2 ($M = 0.53$ *vs.* $0.23\ \mu V$; $p_{Load\ 2-4} = .048$ ($\eta_p^2 = .26$)) but the intermediate Load 3 ($M = 0.29\ \mu V$ $p_{Load\ 2-3} = .644$ ($\eta_p^2 = .05$), $p_{Load\ 3-4} = .124$ ($\eta_p^2 = .18$)) was statistically indistinguishable from the other load conditions. Therefore, as predicted, at higher load levels, where more sustained attention was required, P2 amplitude was largest.

For the N2 component at 270–330 ms (Fig. 2c), ANOVA revealed a modest main effect of load, $F(2, 36) = 4.0$, $p = .026$, $\eta_p^2 = .18$, with post-hoc contrasts showing N2 to be larger for Load 4 than Load 2 ($M = -0.14$ *vs.* $-0.11\ \mu V$; $p_{Load\ 2-4} = .049$ ($\eta_p^2 = .26$)), but the intermediate Load 3 ($M = -0.03\ \mu V$; $p_{Load\ 2-3} = .324$ ($\eta_p^2 = .10$), $p_{Load\ 3-4} = .257$ ($\eta_p^2 = .12$)) was statistically indistinguishable from the other load conditions. Since the N2 component is related to stimulus predictability, the decrease with increasing load was expected.

For the P3 component at 320–470 ms (Fig. 2d), ANOVA indicated a main effect of updating load, $F(2, 36) = 3.8$, $p = .045$, $\varepsilon = .76$, $\eta_p^2 = .18$; however, the amplitude decrease across load levels 2 to 4 ($Ms = 1.61, 1.34, 1.20\ \mu V$, respectively, $p_{Load\ 2-3} = .176$ ($\eta_p^2 = .16$), $p_{Load\ 2-4} = .107$ ($\eta_p^2 = .20$), $p_{Load\ 3-4} = .411$ ($\eta_p^2 = .08$)) was not reflected in any significant pair-wise contrast. Therefore, as expected, at higher load levels, which required more cognitive control, P3 amplitude increased.

The topographies displayed in Fig. 3c show a posterior positivity accompanied by an anterior negativity, corresponding to the old/new subcomponents reflecting recollection and familiarity processes in memory, respectively (Rugg and Curran, 2007; Rugg and Yonelinas, 2003). The anterior component (Fig. 3a), measured in a frontal ROI during 450–950 ms showed a main effect of load, $F(2, 36) = 7.3$, $p = .006$, $\varepsilon = .70$, $\eta_p^2 = .28$, with a significant difference between Load 2 and both Load 3

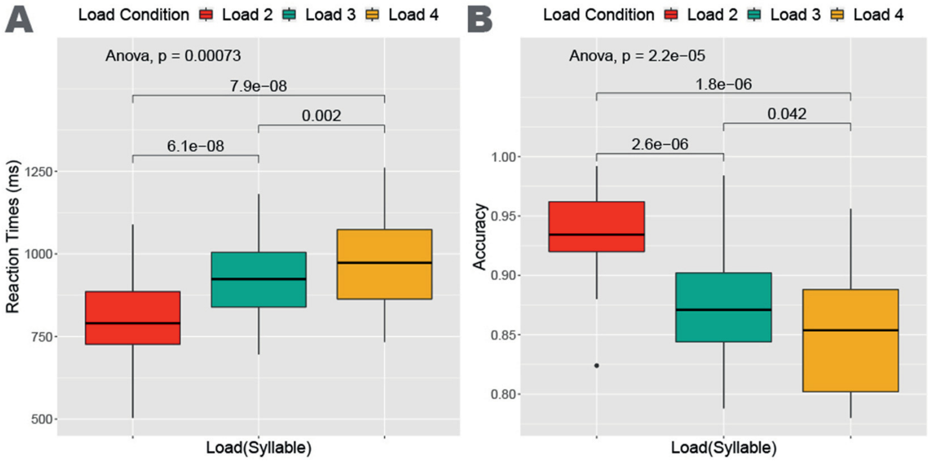


Fig. 1. Bar and whisker plots of performance in Experiment 1. Means as a function of load and contrasts between load conditions are shown for (a) RTs and (b) accuracy.
**p-values in the figure are not corrected for multiple comparisons.*

and Load 4 ($M = -3.0, -2.5$, *vs.* $-2.4\ \mu V$; $p_{\ Load\ 2-3} = .002\ (\eta_p^2 = .47)$, $p_{\ Load\ 2-4} = .03\ (\eta_p^2 = .30)$, $p_{\ Load\ 3-4} = .651\ (\eta_p^2 = .04)$) but not between Load 3 and 4. Notably, the greatest effect size was observed in the time window 460–610 ms, $F(2, 36) = 17.9, p < .001, \varepsilon = .64, \eta_p^2 = .49$, covering the peak of this component.

For the posterior recollection component measured in an asymmetrical posterior ROI, mean amplitude in the 380–530 ms time window decreased from Load 2 to 4 ($M = 2.6, 2.3$, vs. $2.1\ \mu V$), yielding a significant main effect, $F(2, 36) = 9.8, p = .001, \varepsilon = .77, \eta_p^2 = .35$; in post-hoc contrasts the load conditions were ordered Load 2 > Load 3 = Load 4 ($p_{\ Load\ 2-3} = .013\ (\eta_p^2 = .35)$, $p_{\ Load\ 2-4} = .007\ (\eta_p^2 = .39)$, $p_{\ Load\ 3-4} = .187\ (\eta_p^2 = .15)$). Therefore, as predicted, for both frontal and posterior old/new components increasing load decreased amplitude. However, for the frontal component the decrease might be related to lower familiarity, whereas for the posterior component it might be due to the diminished certainty of choice. Interestingly, in the second segment of the posterior component, no load effect was observed, possibly due to a ceiling effect (Vogel and Machizawa, 2004).

Neural sources of the old/new subcomponents were assessed with LORETA in the 400–950 ms window. Fig. 3d shows frontal and parieto-temporal sources for the two-syllable condition, both decreasing from Load 2 to 3 (Fig. 3e). Thus, LORETA confirmed that the old/new complex, which is bipolar at the surface, appears to have at least two separable sources, one originating in the ACC and dorsolateral/orbito-frontal regions and one in parieto-temporal regions.

3. Experiment 2

Experiment 2 explored the consequences of PHSs on updating and their neurocognitive mechanisms. Because in the ERP results of Experiment 1, Load 3 and 4 had been difficult to distinguish, Experiment 2 used the load levels of 1, 2, and 3. We considered Load 1 – essentially a simple counting task – as a useful reference for the higher-load conditions. In other words, as discussed in the introduction, we hypothesized that three important components of the updating function are *storing*, *retrieving*, and *substituting* pieces of information in short-term memory buffers; Load 1 lacks two of these components, that is, *storing* pieces of information that are not immediately relevant, and *retrieving* them when they become relevant, since there is only one piece of information, which is always relevant. For instance, in a two-syllable block, for each tone, participants need to retrieve the previous number of occurrences of that syllable, update it, and if it is not equal to four, store it; for the next tone, they might need to retrieve the number of occurrences of the same syllable or the other one. However, for a Load 1 block, storing and retrieving of information is redundant, as the same number of occurrences is always relevant. Hence, we expected PHS – directed at enhancing updating – to boost performance mainly in Load 2 and 3; therefore, Load 1 also provides a measure of the specificity of PHS.

Based on the introduction and the framework introduced in Experiment 1, if PHS affects top-down processes, we expected it to enhance task performance. Furthermore, the P2 and P3 components of the ERP, related to the engagement of attentional resources and EFs, respectively, should increase due to PHS. In addition, the posterior old-new component, which has been related to the activities of WM buffers, should be modulated by PHS. However, if PHS unexpectedly affects bottom-up mechanisms, these effects might be associated with, either, irrelevant and distracting stimuli, or with task-relevant stimuli. In case that PHS affects task-irrelevant stimuli, performance might be enhanced, and only ERP components that are related to the perception of stimuli and stimulus properties, shall be affected, that is, N1, N2, and the frontal familiarity component; however, ERP components related to top-down processes should be unaffected. In case that – unexpectedly – task-relevant stimuli will be blocked by PHS, or an inflexible response will be developed, performance should decline; therefore, this case should be easily distinguished from other scenarios.

3.1. *Method*

3.1.1. *Participants*

As it is commonly held that PHS mainly affects highly hypnotizable participants (e.g., Iani et al., 2009; Iani et al., 2006; Raz et al., 2005), we screened a large number of volunteers ($N = 477$; $Cronbach's\ \alpha_{\ Objective\ items} = .67$; $Cronbach's\ \alpha_{\ Subjective\ items} = .90$)with the German version of the Harvard group scale of hypnotic susceptibility (HGSHS) (Bongartz, 1985); the results of HGSHS-A are the subject of another study (Zahedi and Sommer, in prep). Notably, even though reliability of the HGSHS-A has been confirmed by a relatively high degree of stability (Piccione et al., 1989), its construct validity is debated (McConkey et al., 1980). Participants were invited to screening sessions via eBay small ads, flyers, and email lists. From a total of 157 screened individuals, 21 highly hypnotizable ones (score $> 9/12$) agreed to take part in the experiment. Two participants had to be excluded

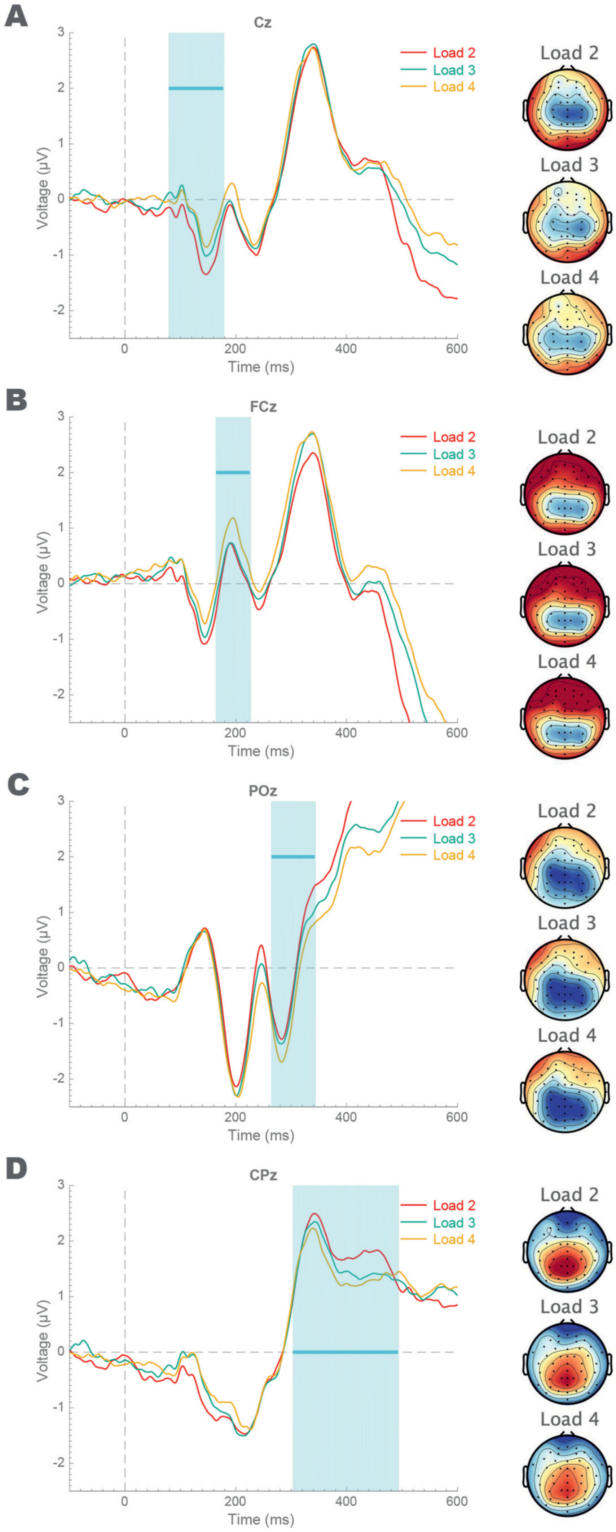


Fig. 2. Grand average ERPs superimposed for different load conditions. Shaded areas show the time windows during which load effects for the targeted components were significant. Left: ERPs at representative electrodes. Right: topographies for these components at different load conditions; (a) N1 (80–180 ms; map scaling: −1.0 to 1.0 μV); (b) P2 (165–215 ms; map scaling: −2 to 1.5 μV); (c) N2 (270–330 ms; map scaling: −1 to 2 μV); (d) P3 (320–470 ms; map scaling: −2 to 2 μV).

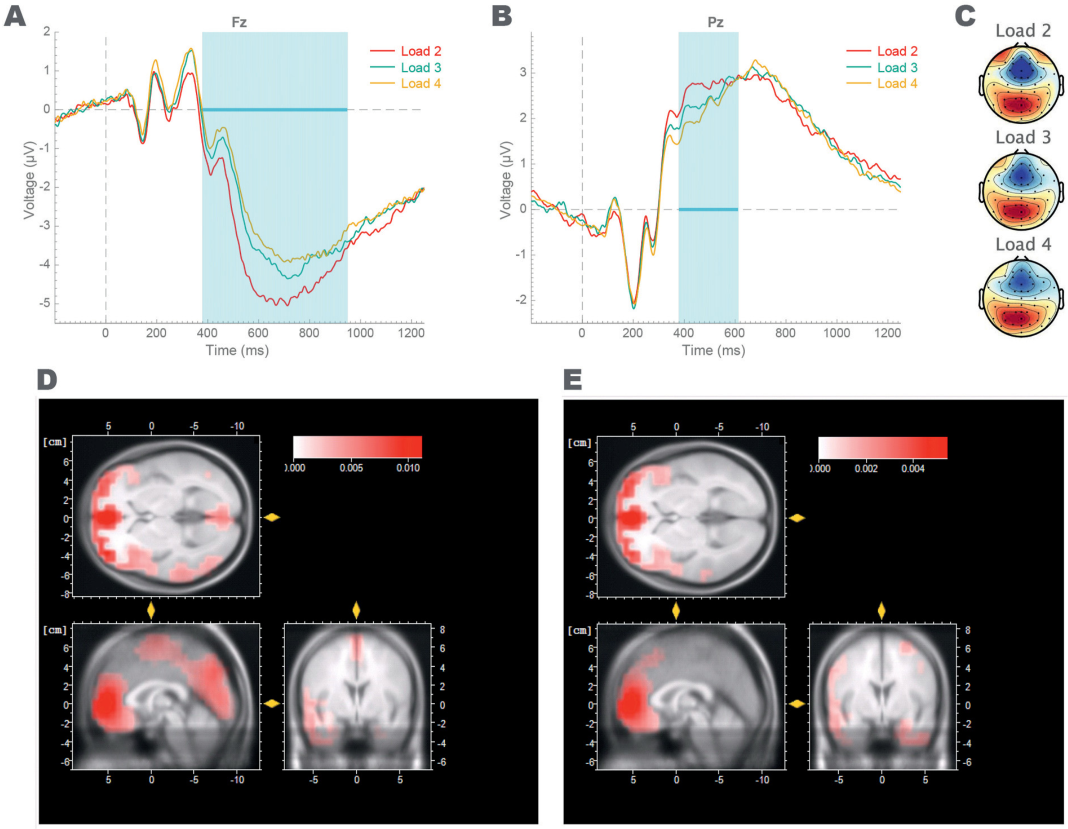


Fig. 3. Grand average ERPs of the old/new components. (a) The anterior and (b) the posterior old/new components: ERPs superimposed for different load conditions. Shaded areas show the time windows during which load effects were present. (c) Topographies for these components across load conditions during the 400–900 ms time windows (map scaling: −3 to 3 μV). Bottom. LORETA source localization during the 400–900 ms time window for (d) the Load 2 condition and (e) Load 2 minus Load 3 condition.

because they did not show up for Session 2, and another participant terminated the hypnosis procedure in Session 1, resulting in a final sample of 18 (11 females; $M = 26.83$ *years*; *range* $= 20 - 39$, $SD = 6.53$). Remuneration and ethics approval were the same as for Experiment 1.

The sample size of Experiment 2 ($n = 18$) was based on a power analysis with expected effect sizes (Cohen's $f = .40$ equivalent to $\eta_p^2 = .14$) derived from Experiment 1, and our previous studies (e.g., Zahedi et al., 2019; Zahedi et al., 2017); the estimated power (Faul et al., 2007; Kreidler et al., 2013) for both RTs and ERPs was above recommended values, $1 - \beta > 0.90$ (Cohen, 1988, 2016).

3.1.2. Hypnosis and posthypnotic suggestions (PHS)

Participants received hypnosis plus PHS while sitting in an easy chair outside of the experimental chamber. In case that PHS was applied in Session 1, participants were familiarized with the task before hypnosis in order to allow a narrative reference during PHS.

The hypnosis procedure, consisting in induction, deepening, suggestion, and termination phases (Hammond, 1998), was identical for all participants. For induction, the one-two-three technique was used (Hammond, 1990, 1998), which was followed by multiple deepening suggestions, including progressive muscular relaxation, and multiple imagination techniques (Hammond, 1990, 1998; Shor and Orne, 1962). After induction of hypnosis and deepening, the following PHS (given here in translation, originally in German) was provided:

Imagine our experimental room. As soon as you see the room, please open its door and go inside. Please sit on the chair in front of the table. As you are looking at the monitor, the same task as you did before, will appear on the monitor; please follow the task instructions and respond as fast and accurately as possible. After you hear a bell ringing, a four-digit number will appear in your mind. Each digit in the number corresponds to one of the buttons. With each tone, the corresponding digit will increase by one without any effort on your side, fully automatically. Every time one of the digits reaches the number 4, press the corresponding button and the digit will return to zero. The process will be effortless, and the number will always be clearly present in your mind. Please continue until you are confident that the number is always in your mind and will be updated effortlessly. After the second bell-ring everything returns to how it was before the first ring, like you have never had this capability.

PHS was presented interactively, that is, after each section of the suggestion, the hypnotist waited for a confirmation from the participant, before moving to the next section. After PHS, hypnosis was terminated with the countdown technique similar to the one used in the HGSHS-A (Shor and Orne, 1962).

Importantly, PHS suggested the same visual strategy as the task instructions, given at the beginning of both Experiments 1 and 2, that is, we asked participants to associate syllables with numbers and mentally form a four-digit number and update its digits as more syllables are presented; further, participants were advised to use this strategy and to refrain from using any other strategies such as counting with fingers.

3.1.3. EEG recordings and ERP analyses

EEG recordings and ERP analyses were identical to Experiment 1. We used the same ROIs as for Experiment 1 with one exception: as the P3 component in Experiment 2 was more central in comparison to Experiment 1, we added FC1, FCz and FC2 electrodes to the P3 ROI (i.e., FC1, FCz, FC2, C3, Cz, C4, CP3, CPz, CP4, P1, Pz and P2 electrodes).

3.1.4. Design and procedure

The second study included two sessions, one with hypnosis plus PHS and the other one without hypnosis. The two sessions were administered in counterbalanced order across participants, meaning, participants were assigned to the NH-PHS or the PHS-NH orders. Each session started with EEG preparation. Thereafter, in the PHS session, hypnosis plus PHS was administered, followed by a 5-min rest and the task. In the NH session, EEG preparation was immediately followed by the task. In both sessions, participants performed two practice blocks at the beginning of the task; practice blocks were excluded from analyses. In total, sessions with hypnosis plus PHS took around 3 h and sessions without hypnosis 2.5 h.

3.2. Results and discussion

3.2.1. Performance

Fig. 4 shows performance as a function of load and PHS conditions. For analyzing the RTs and accuracy data, ANOVAs with load (Load 1, 2, and 3) and PHS (NH, PHS) as within-subject, and order as between-subject factors (NH-PHS vs. PHS-NH) were calculated. Corrections for multiple testing were the same as in Experiment 1. ANOVA of RTs (Fig. 4a) confirmed main effects of load, $F(2, 32) = 108.3$, $p < .001$, $\varepsilon = .57$, $\eta_p^2 = .87$, and PHS, $F(1, 16) = 9.5$, $p = .006$, $\eta_p^2 = .37$, and marginally confirmed their interaction, $F(2, 32) = 3.3$, $p = .055$, $\varepsilon = .89$, $\eta_p^2 = .17$. The effect of order was not significant, $F(1, 16) = .01$, $p = .903$, $\eta_p^2 = .00$. Planned contrasts (Fig. 4b) showed that, although mean RTs did not differ significantly between the NH and PHS sessions for Load 1, $F(1, 16) = .07$, $p = .793$, $\eta_p^2 = .00$, they did for both Load 2, $F(1, 16) = 9.4$, $p = .007$, $\eta_p^2 = .37$, Cohen's $d = .71$, and Load 3, $F(1, 16) = 14.2$, $p = .001$, $\eta_p^2 = .47$, Cohen's $d = .87$. Notably, after dropping Load 1 from factor load, ANOVA still showed main effects of PHS, $F(1, 16) = 14.5$, $p = .001$, $\eta_p^2 = .47$, and load, $F(1, 16) = 206.7$, $p < .001$, $\eta_p^2 = .92$, but no significant interaction of these factors, $F(1, 16) = .08$, $p = .780$, $\eta_p^2 = .00$. The effect of order was again not significant, $F(1, 16) = .99$, $p = .329$, $\eta_p^2 = .05$.

ANOVA of accuracy (Fig. 4c) confirmed main effects of load, $F(2, 32) = 23.4$, $p < .001$, $\varepsilon = .65$, $\eta_p^2 = .59$, and PHS, $F(1, 16) = 10.2$, $p = .005$, $\varepsilon = .66$, $\eta_p^2 = .39$, and marginally confirmed their interaction, $F(2, 32) = 3.6$, $p = .057$, $\varepsilon = .69$, $\eta_p^2 = .18$. The effect of order was not significant, $F(1, 16) = .94$, $p = .245$, $\eta_p^2 = .05$. In planned contrasts (Fig. 4d), the PHS effect was not significant for Load 1, $F(1, 16) = .08$, $p = .774$, $\eta_p^2 = .00$, but it was for Load 2, $F(1, 16) = 4.4$, $p = .050$, $\eta_p^2 = .21$, Cohen's $d = .51$, and Load 3, $F(1, 16) = 24.0$, $p < .001$, $\eta_p^2 = .60$, Cohen's $d = 1.18$. Again, after excluding Load 1 from ANOVA, there were main effects of both PHS, $F(1, 16) = 15.4$, $p = .001$, $\eta_p^2 = .49$, and load, $F(1, 16) = 70.9$, $p < .001$, $\eta_p^2 = .81$, for accuracy but no significant interaction, $F(1, 16) = .08$, $p = .780$, $\eta_p^2 < .01$. The effect of order was again not significant, $F(1, 16) = 1.1$, $p = .329$, $\eta_p^2 = .05$.

Together, as in Experiment 1, higher load increased RTs and diminished accuracy; however, PHS counteracted these effects at Loads 2 and 3. Therefore, besides replicating results of Experiment 1, that is, showing that the tone-monitoring task is sensitive to updating load and hence reflects the updating function, the enhancements in performance due to PHS support the hypothesis that PHS improves top-down processes. Notably, the effect sizes reported in the current study are comparable with other studies measuring effects of PHSs on WM (e.g., Lindelov et al., 2017), and inhibition (e.g., Iani et al., 2006; Raz et al., 2006; Zahedi et al., 2019).

3.2.2. Event-related brain potentials

Since order as a between-subject factor had not affected performance significantly, it was not included in the ANOVAs of ERPs, which otherwise were the same as for the performance data. As shown in Figs. 5 and 6, as compared to Load 2 and 3, Load 1 elicited very different ERP waveforms, confirming the idea that Load 1 and the higher-load conditions substantially differed in the processes involved. As we hypothesized that Load 1 does not measure the updating functions, we dropped Load 1 from ANOVAs where we wanted to show effects of PHS and used only Load 2 and 3 for the factor load.

For N1 amplitude in the 120–180 ms time window (Fig. 5a), ANOVA revealed a main effect of load, $F(2, 34) = 4.4$, $p = .035$, $\varepsilon = .73$, $\eta_p^2 = .21$; N1 amplitudes across load conditions were ordered as follows, $|Load\ 1| = |Load\ 2| > |Load\ 3|$ ($M = -0.8, -0.8$ *vs.* $-0.5\ \mu V$; $p_{Load\ 1-2} = .997$ ($\eta_p^2 < .01$), $p_{Load\ 1-3} = .134$ ($\eta_p^2 = .19$), $p_{Load\ 2-3} = .001$ ($\eta_p^2 = .52$)), fully replicating the corresponding difference between Loads 2 and 3 in Experiment 1. There was neither a significant main effect of PHS, $F(1, 17) = 1.2$, $p = .282$, $\eta_p^2 = .06$, nor significant interaction with load $F(2, 34) = .92$, $p = .406$, $\varepsilon = .98$, $\eta_p^2 = .05$.

Therefore, as expected, the N1 component in ERPs decreased in

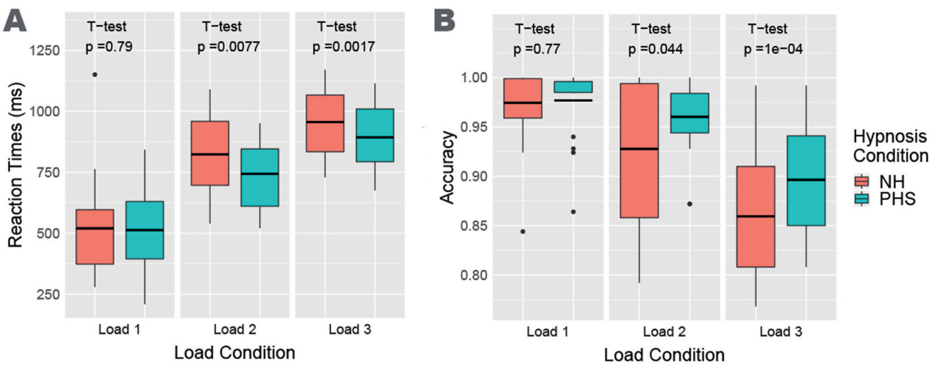


Fig. 4. Performance in Experiment 2 as a function of updating load and PHS conditions (no-hypnosis (NH), hypnosis plus posthypnotic suggestion (PHS)), and contrast tests between PHS conditions across load, shown for (a) RTs and (b) accuracy.

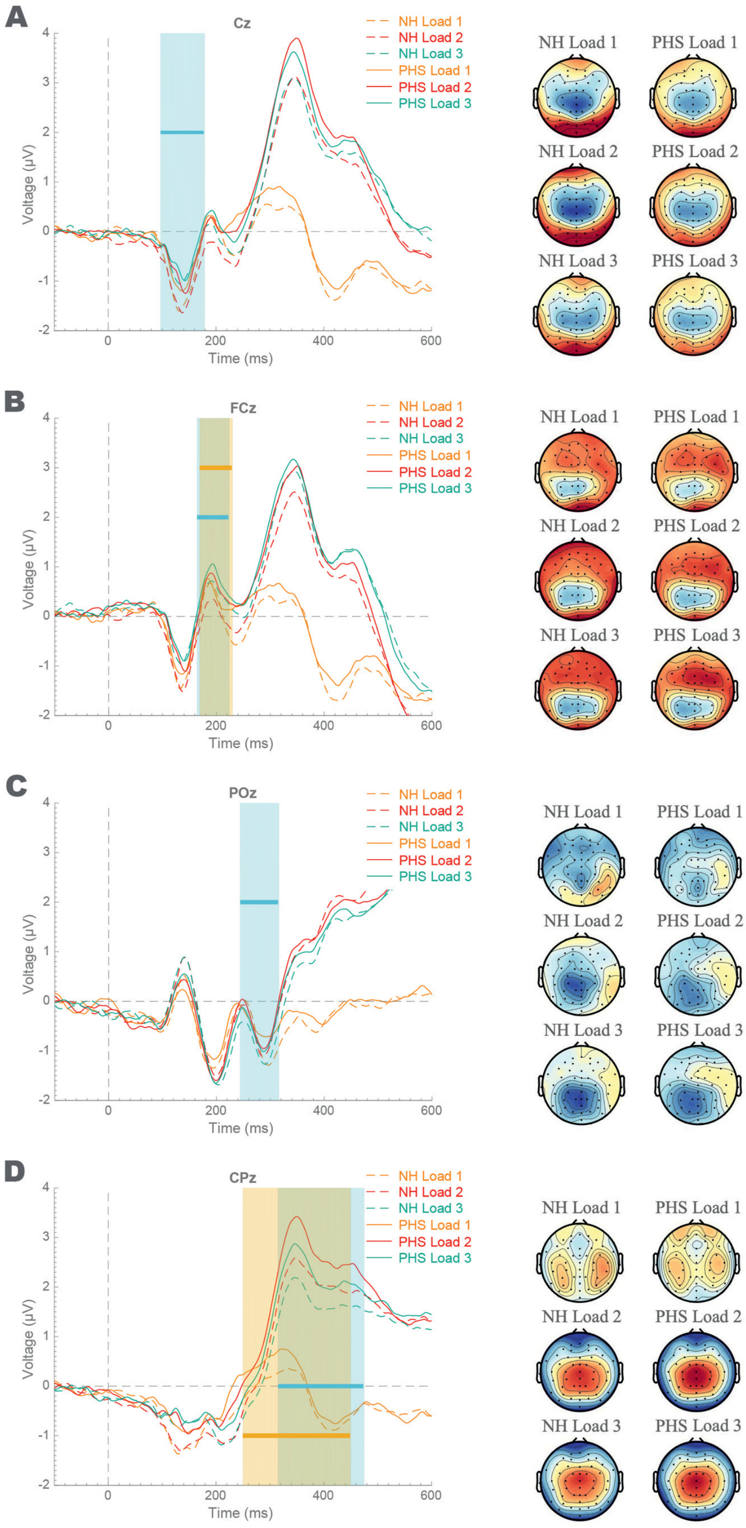


Fig. 5. Left. Grand average ERPs superimposed for different load conditions. Cyan and yellow areas show the time windows during which load and PHS effects respectively, were present for the targeted components. Right. Topographies for these components across different load and PHS conditions; (a) N1 (120–180 ms; map scaling: −1 to 1 μV); (b) P2 (175–225 ms; map scaling: −2 to 1 μV); (c) N2 (250–310 ms; map scaling: −1 to 2 μV); (d) P3 (300–450 ms; map scaling: −2.5 to 2.5 μV). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

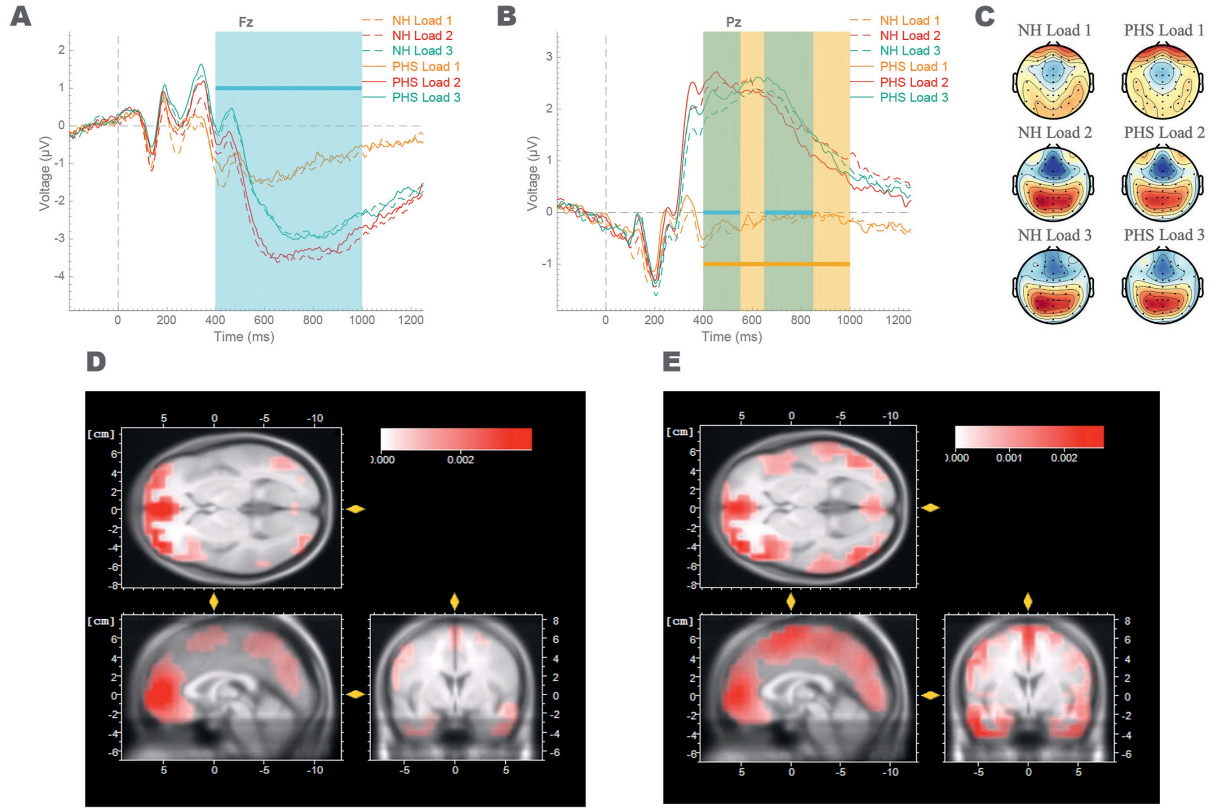


Fig. 6. Grand average ERPs of the old/new components. (a) The anterior and (b) the posterior old/new components: ERPs superimposed for different load conditions. Cyan and yellow shaded areas show the time window during which load and interaction between load and PHS effects, respectively, were present. (c) Topographies for these components across load conditions at the 400–900 ms time windows; (map scaling: −2.5 to 2.5 μV). Bottom: LORETA source localization during 400–900 ms time window for (d) the load effect of the NH condition (Load 3 minus Load 2) and (e) the PHS effect at Load 3 (PHS minus NH). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

amplitude with increasing load in both experiments, conforming with results from n-back tasks (e.g., Frtusova et al., 2013; Han et al., 2013; Hillyard and Anllo-Vento, 1998). This amplitude reduction probably reflects the perceptual changes if several targets have to be monitored in parallel. Interestingly, the effect was unaffected by PHS, in line with the idea that PHS does not affect bottom-up processes.

The P2 component was a rather small – sometimes only relative - positivity (Fig. 5b) but in the 175–225 ms time window, ANOVA showed a main effect of load, $F(2,34) = 3.6, p = .048, \eta_p^2 = .17$, and PHS, $F(1,17) = 6.9, p = .017, \eta_p^2 = .27$, but no significant interaction between these factors , $F(2, 34) = 1.8$, $p = .174$, $\eta_p^2 = .10$. Load 1 ($M = -0.01$; $p_{Load\ 1-2} = .083$ ($\eta_p^2 = .23$), $p_{Load\ 1-3} = .95$ ($\eta_p^2 < .01$)) was indistinguishable from the other conditions. ANOVA with just Load 2 and 3 showed a significant increase in amplitude of this relative positivity from Load 2 to Load 3 ($M = -0.20$ *vs.* $-0.03\ \mu V$), $F(1, 17) = 7.2$, $p = .001$, $\eta_p^2 = .29$. Further, independent of updating load, PHS increased P2 amplitude over NH ($M = 0.04$ *vs.* $-0.21\ \mu V$), $F(1, 17) = 7.3$, $p = .014$, $\eta_p^2 = .30$.

In both experiments, the P2 component increased due to updating load and – in Experiment 2 – also due to PHS. At first glance, this might seem puzzling as PHS enhanced performance, whereas load diminished it. Based on the theoretical framework introduced for Experiment 1, we expected P2 amplitude to increase with higher updating load, since several studies with other tasks (e.g., Dunn et al., 1998; Han et al., 2013) have suggested that in conditions requiring more sustained attention P2 amplitude increased. This expectation was met in both present experiments. Further, we expected PHS to increase P2 amplitude, only if PHS causes higher recruitment of attentional resources and EFs. Therefore, unidirectional modulations of P2 amplitude by updating load and PHS might be related to a common underlying mechanism, that is, higher sustained attention. This explanation reconciles the apparent contradiction because the deployment of sustained attention (partially) counteracted the rising demands of increasing load and successfully improved performance during PHS. Please note that in this account, sustained attention is conceived as a top-down process.

ANOVA of N2 amplitude (Fig. 5c) during 250–310 ms showed a main effect of load, $F(2, 34) = 4.4$, $p = .027, \varepsilon = .82$, $\eta_p^2 = .20$, with *Load* 1 = *Load* 2 < *Load* 3 ($M = 0.2$, -0.0, *vs.* $-0.3\ \mu V$; $p_{Load\ 1-2} = .506$ ($\eta_p^2 = .07$), $p_{Load\ 1-3} = .042$ ($\eta_p^2 = .29$), $p_{Load\ 2-3} = .049$ ($\eta_p^2 = .27$)), but there was neither a significant main effect of PHS, $F(1, 17) = .63$, $p = .437$, $\eta_p^2 = .03$, nor a significant interaction with load, $F(2, 34) = 1.6$, $p = .228$, $\varepsilon = .94$, $\eta_p^2 = .08$.

Since the posterior N2, as assessed in the present experiments, has been related to stimulus predictability (Folstein and Van Petten, 2008), we expected increasing updating load to increase N2 amplitude, which was indeed observed in both experiments. The absence of any effect of PHS on N2 further corroborates that PHS does not significantly affect the perception of stimuli or their properties due to bottom-up influences, as also seen in N1 amplitude.

For P3 amplitude during the 300–450 ms window (Fig. 5d), ANOVA showed a very strong load effect, $F(2, 34) = 33.1$, $p < .001$, $\varepsilon = .55$, $\eta_p^2 = .66$, with an inverted U-shaped ordering: *Load* 1 < *Load* 2 > *Load* 3 ($M = -0.1$, 1.9 *vs*. 1.6 μV; $p_{Load\ 1-2} < .001$ ($\eta_p^2 = .67$), $p_{Load\ 1-3} < 001$ ($\eta_p^2 = .65$), $p_{Load\ 2-3} = .048$ ($\eta_p^2 = .25$)). In addition, there was an increase of P3 amplitude from NH to PHS ($M = 1.00$ *vs*. 1.4 μV), reflected in a main effect of PHS, $F(1, 17) = 4.8$, $p = .041$, $\eta_p^2 = .22$, (Fig. 5d). Importantly, there was no significant interaction, $F(2, 34) = .57$, $p = .608$, $\varepsilon = .49$, $\eta_p^2 = .03$, indicating that the PHS-induced changes in P3 amplitude did not depend on updating load.

The P3 component marks the time window during which the updating function is implemented (Polich, 2007). As the efficiency of EFs (here, updating) should decrease with higher demands (Diamond, 2013), we expected the P3 component to decrease with increasing load; in addition, the increase of P3 due to PHS supports the idea that PHS works as an efficient mental practice, enhancing the effective implementation of EFs. Interestingly, in Load 1, the P3 component was very small. If we consider that P3 has been related to the updating function (Donchin and Coles, 1988) one might expect a pronounced P3 mainly in higher load conditions (i.e., Load 2 and 3), where updating is indeed required.

Finally, we analyzed the anterior and posterior old/new components (Fig. 6). Here, we excluded Load 1 from all analyses as this condition is fundamentally different from the other load levels. The anterior familiarity-related component during the 420–920 ms window (Fig. 6a) neither showed a significant main effect of PHS, $F(1, 17) = .14$, $p = .712$, $\eta_p^2 < .01$, nor significant interaction between PHS and load, $F(1, 17) = .84$, $p = .371$, $\eta_p^2 = .04$, but there was a main effect of load, $F(1, 17) = 11.3$, $p = .003$, $\eta_p^2 = .40$; the strongest effect of load was observed during 460–610 ms, $F(1, 17) = 21.3$, $p < .001$, $\eta_p^2 = .55$, covering the peak of this component.

Therefore, as expected, decreasing familiarity with individual syllables as updating load was increased is reflected in the load effect on this component. Further, if PHS affects top-down processes, for instance, a more efficient mental manipulation of a visual counter, it should not affect the familiarity of individual syllables, and hence, the frontal old/new component would not be affected by PHS. Therefore, the absence of a significant PHS effect on the frontal familiarity component further supports the idea that PHS only affects top-down regulation.

The parietal recollection-related component during the 400–550 ms time window (Fig. 6b), showed a load effect, $F(1, 17) = 4.5$, $p = .048$, $\eta_p^2 = .21$, but neither PHS effect, $F(1, 17) = .14$, $p = .706$, $\eta_p^2 < .01$, nor interaction between these factors, $F(1, 17) = 1.8$, $p = .188$, $\eta_p^2 = .09$, were significant. In addition, during 670–820 ms, there was a load effect, $F(1, 17) = 4.8$, $p = .044$, $\eta_p^2 = .22$, and an interaction of load and PHS, $F(1, 17) = 4.5$, $p = .048$, $\eta_p^2 = .20$, but no significant main effect of PHS, $F(1, 17) = .36$, $p = .553$, $\eta_p^2 = .02$. Further, there was an interaction between PHS and load during 500–1000 ms time window (NH vs. PHS at Load 2: $M = 1.91$ *vs*. 1.53 μV; at Load 3: 1.90 *vs*. 1.82 μV), $F(1, 17) = 6.7$, $p = .019$, $\eta_p^2 = .28$, but no significant main effects of PHS, $F(1, 17) = .66$, $p = .427$, $\eta_p^2 = .03$, or load, $F(1, 17) = 1.7$, $p = .205$, $\eta_p^2 = .09$. Hence, PHS reduced the recollection component, especially at Load 2.

It is important to consider that the memory literature (Rugg and Curran, 2007; Wilding and Ranganath, 2011), reports a peak around 600–700 ms time window that increases with deeper processing of the stimuli. In Experiment 1 and in the NH condition of Experiment 2, we found a load effect only in the first segment of this component but not in the later segment (around 600–700 ms), possibly indicating a ceiling effect on the second segment, as all materials were studied with maximum effort in both of these hard conditions. Our results are in line with the prediction that if PHS enhances the implementation of cognitive control and, hence, decreases demands on short-term memory buffers, it affects the posterior recollection component. This relief from demands was most beneficial for medium Load 2, strongly reducing the posterior old/new component. In contrast, Load 3 still maintained pronounced demands on short-term memory buffers, limiting the reduction of the component.

LORETA results for the memory-related ERP components are shown in Fig. 6d–e. The results confirm those from Experiment 1 that load-sensitive sources are distributed at frontal and parieto-temporal brain regions. Conforming with the surface ERPs, the alterations in neural activities due to PHS in comparison with NH seem to be more pronounced at parietal than at frontal regions. Therefore, Experiment 2 not only replicated the source configuration of Experiment 1 but also revealed widespread, predominantly parietal modulations due to PHS during the 400–900 ms time window. Notably, our ERP results at the surface are in line with source localization as it showed for the frontal negative-going aspect both, a larger amplitude difference across load levels as well as bigger load effects than for the posterior positive-going aspect. This distribution of information and cognitive-processing over both frontal and parietal areas is in line with fMRI results of Ester et al. (2015) that both regions are involved in cognitive control and hold short-term memory buffers.

4. General discussion

We probed the updating function in WM with the tone-monitoring task in two experiments and explored its possible modification by appropriately tailored PHS, that is, suggesting the same cognitive strategy as contained in the task instructions. Experiment 1 demonstrated that ERP effects of updating load consistently resembled those in other memory tasks (e.g., Brouwer et al., 2012; Frtusova et al., 2013; Han et al., 2013; Nakao et al., 2012; Rugg and Curran, 2007; Rugg and Yonelinas, 2003; Scharinger et al., 2017; Watter et al., 2001). Experiment 2 demonstrated that PHS can substantially boost WM performance, while ERPs revealed both general and memory-related mechanisms underlying these improvements.

4.1. Working memory and its neuronal correlates

Utilizing the tone-monitoring task for taxing the updating function in two experiments, we established that increasing updating load prolonged response latency (RT) and diminished accuracy. Further, our ERP results showed that the usual components observed in n-back tasks are also present during tone-monitoring, that is, the N1, N2 P2, P3, frontal familiarity and posterior recollection components were all updating load-sensitive. Interestingly, there was an important difference between our two tone-monitoring experiments. In Experiment 1, Loads 2, 3, and 4 were used, whereas, in Experiment 2, we used Loads 1, 2, and 3. The Load 1 condition is superficially isomorphic with the other load conditions, that is, it requires the same auditory input and manual output. However, Load 1 lacks an important aspect of updating, that is, simultaneously working on several streams of information, essentially turning it into a simple counting task. In other words, Load 1 does not need constant storing and retrieving of different pieces of information in short-term memory buffers but only substituting the same piece of information, which is always relevant. Hence, storing and retrieving in short-term memory buffers is not required in Load 1. Our ERP results showed that even though the perceptional components, such as N1 and N2 were also triggered by Load 1, no substantial P3 or posterior recollection component was elicited. This observation has two implications; first, it highlights P3 as a component which is correlated with the incorporation of EFs – here, updating – (for review please see Polich, 2007) and the posterior recollection component, which is related to the storing and retrieving of different pieces of information in short-term memory buffers (in line with e.g., Vogel and Machizawa, 2004). Second, the observation highlights the importance of handling several pieces of information for the updating function to be relevant in a task, and shows that besides substituting, also storing and retrieving of different pieces of information in short-term memory are integral to the updating function. Interestingly, in all tasks singled out by Miyake et al. (2000) as measuring updating, that is, tone-monitoring, keep-tracking, and letter-memory, *storing* and *retrieving* of information in short-term memory buffers are necessary.

4.2. PHS effects: alterations in bottom-up processes or top-down regulation?

As one of the main aims of the current study, we investigated the underlying mechanisms of PHS effects on cognition. A study containing hypnotic suggestions and PHSs can investigate three different concepts, to be named, effects of hypnosis, suggestions, and cognitive strategies. In the current study, we attempted to isolate the effects of suggestions. That means, we asked high-hypnotizable participants in two different conditions, that is, in the NH and PHS conditions, to implement the same visual strategy. The only difference between the two conditions was that participants received the strategy either as the task instruction alone or in combination with PHS. One should keep in mind that suggestions contain also other components besides strategies. For instance, our PHS asked participants to *imagine* doing the task, *use* the suggested visual strategy, and *continue to apply* the strategy until they become so adept at using it that it can be implemented effortlessly. Therefore, in the current study, we investigated the effects of suggestions but not hypnosis or cognitive strategies per se. This contrasts, for instance, with a study by Parris and Dienes (2013) who investigated the effects of hypnosis where they compared the effects of suggestions in a non-hypnotic context with the effects of the same suggestions when presented as PHS. As an example for a study on the effects of cognitive strategies, Galea et al. (2010) first asked high-hypnotizable participants to feel rigidity and stiffness in their arms, and then, to move their arms with the implication that they cannot do it. As discussed by the authors, there are several strategies that participants might have used to achieve this goal; for instance, participants might have thought about the movement but blocked its execution, or they might have initiated the action but simultaneously counteracted it. Hence, Galea et al. (2010) were presenting a goal, asking participants to achieve it without suggesting any special strategy, and investigated different strategies that can be used for achieving the goal. In contrast to these studies, our primary aim was to isolate the effects of PHSs on task performance.

PHS in Experiment 2 substantially boosted updating in WM. According to conventional standards, the effect size of the performance improvement was medium to large for Load 2 and large for the more difficult Load 3 condition. Interestingly, for Load 1 in Experiment 2, the performance was not significantly affected by PHS. The absence of significant PHS effects in Load 1 supports the selectivity of PHS to updating requirements, in other words, PHS did not affect performance in general, but specifically the updating function. However, as performance in Load 1 even without hypnosis was almost perfect, the non-existence of significant effects can be related to a ceiling effect in this very easy condition, merely requiring counting with very little load on WM. Therefore, arguments regarding this condition must be treated cautiously. Further, PHS affected two categories of ERP components. First, PHS increased ERP components that are related to the recruitment of EFs and attentional resources, that is, P2 and P3. Second, PHS modulated the posterior recollection component, which is related to the activities of WM buffers. Based on our hypotheses, we expected PHS to enhance performance and affect the ERP components related to recruitment of EFs and WM buffers only if PHS effects are mediated through top-down regulation.

Can any changes in bottom-up processes also explain our results? One may argue that if PHSs would affect bottom-up processes, for instance, blocking distracting stimuli, it might also improve performance in an updating task. However, it must be considered that our sessions were conducted under experimental control, in a sound-attenuated and visually shielded chamber, minimizing distraction, and task duration was relatively short, preventing fatigue. In addition, changes in perception due to PHSs affecting bottom-up processes are unlikely, since all stimuli were very clear and easy to distinguish, and very little background noise was present during task completion. Therefore, there seems to be little room to enhance perception. Furthermore, the ERP results did not reveal any changes in N1 amplitude, a marker of auditory perception, rendering changes in bottom-up processes unlikely. In contrast, some alterations in late ERP components, which occurred due to PHSs, are hard to explain by changes in bottom-up processes alone but are plausible consequences of top-down processes. Therefore, our results are largely in line and corroborating the hypothesis that enhancements in the WM function were due to the more efficient utilization of proactive control. Together, even though the changes in bottom-up processes as a contributor to performance improvements by PHS cannot be ruled out completely, even if present, due to the setting of the experiment and the invariance of early ERP components, the effects are likely minimal.

At this point, the dichotomy of top-down regulation versus decoupling of cognitive control from cognitive monitoring processes should be reconsidered. As discussed in the introduction, in contrast to the top-down account, which was originally devised to explain effects of PHSs, the decoupling account was primarily devised to explain the effects of pure hypnosis and not suggestions per se, and hence, it was based on studies, which observed that hypnosis alone, when not involving task-relevant suggestions, can deteriorate performance (e.g., Sheehan et al., 1988). First, these observations are challenged by findings that hypnosis alone does not necessarily affect task performance and its neural correlates (Zahedi et al., 2017), or may enhance performance, for example in the implicit serial reaction-time (SRT) task (Nemeth et al., 2013). Even though Nemeth et al. (2013) tried to relate their results to the decoupling account, the cognitive control literature repeatedly showed that learning in SRT tasks depends on cooperation of cognitive control and monitoring (e.g., Gobel et al., 2011; van der Graaf et al., 2006). With respect to the effects of hypnotic suggestions and PHSs, the decoupling account is even more restricted; as discussed in the introduction, the decoupling account can only associate the enhancements in performance due to PHSs to changes in bottom-up processes, which, considering our behavioral and neural data is unlikely. Our study, in line with the suggestion of Terhune et al. (2017), strongly corroborates the hypothesis that effects of hypnotic suggestions and PHSs are best explained by enhanced utilization of top-down regulation. In line with our argument, Tobis and Kihlstrom (2010) showed that the effects of PHS cannot be understood in terms of developing automatic and reflexive responses; instead, PHS behaviors are best explained as resource-consuming actions, dependent on top-down regulation.

4.3. Can PHS effects be related to mental imagery boosting mental practice?

A fundamental, but often neglected question in the hypnosis literature is, how PHSs affect top-down processes (Terhune et al., 2017). In the introduction, we discussed the suggestion of Egner and Raz (2007) that PHSs effects in Stroop tasks may resemble a contention scheduling system and its problem to explain the development and efficacy of a competing schema. Especially, learning a new response is not congruent with the decoupling account as learning requires the coordination between cognitive control and monitoring (e.g., Gobel et al., 2011; van der Graaf et al., 2006). Now that our results support top-down regulation as a plausible mediator of PHS effects, we can revisit the suggestion of Egner and Raz (2007).

The first question is whether learning a new trigger-action association can boost performance in both inhibition and updating tasks. As discussed, in inhibition tasks, a second well-learned trigger-action association, which can compete with automatic but inappropriate responses, will make participants capable to exert inhibition more efficiently and fruitfully and therefore, enhance their performance (e.g., Dulaney and Rogers, 1994; Protopapas et al., 2014). But how about updating? In updating tasks, it has been shown that extensive training can enhance performance but will not increase WM capacity (Diamond and Ling, 2016); hence, a well-learned response empowers participants to utilize their cognitive control in a more efficient manner. The second question is, how PHSs enable participants to learn a new strategy? As discussed in the introduction, the sociocognitive perspective defines hypnosis as an "imaginative experience" (Lynn et al., 2015). Then, PHSs can be framed as an imagery technique boosting mental practice of the presented strategy in the targeted task. That means, PHSs boost a cognitive simulation of the targeted task, where participants can apply the presented cognitive strategy (or in case that no strategy has been given, finding an applicable cognitive strategy and using it), and hence, learn a trigger-action contingency and reinforce it until it can be efficiently used. Two points must be considered here; first, the cognitive simulation theory has shown "imagining perceiving something is essentially the same as actually perceiving it" (Hesslow, 2002), and therefore, imagining the task and applying the strategy is a powerful and efficient way to practice a trigger-action contingency, Second, it has been shown that the successful application of mental practice can enhance physical or cognitive skill-learning-procedures (e.g., Frank et al., 2015; Stefanidis et al., 2017).

However, there still remains the question, if PHSs boost mental practice, why are their effects restricted to the condition, during which they are activated, and vanish after they are deactivated? It has been repeatedly shown that learning can be context-dependent, especially if learned responses are not extensively practiced. For instance, Abrahamse and Verwey (2008) have shown that changing the context causes participants to inhibit learned responses. In addition, Ruitenberg et al. (2012) showed that changing contextual cues can be detrimental to learned responses, especially if practice time is limited. As our results indicate and as also discussed by Tobis and Kihlstrom (2010), PHSs do not cause an automatic response to be formed, and therefore, contextual dependencies are important.

Can the present behavioral and ERP results corroborate our suggestion that imagery techniques involved in PHSs boost mental practice, helping participants to develop a well-learned and context-dependent response? Here we need to look at the ERP modulation by PHS from a different perspective. We found two types of neurocognitive mechanisms of PHS; the first type was independent of load, to be seen in the P2 and P3 components, possibly reflecting proactive control (Braver, 2012). Thus, PHS may have proactively recruited control-related attention, as reflected in the P2 component, and updating-related cognitive control, as reflected in the P3 component. These load-independent PHS effects are in line with the hypothesis that imagery techniques involved in PHS facilitate mental practice. This hypothesis is supported by observations that (1) WM training in auditory feedback tasks increased P2 amplitude (Li et al., 2015), and (2) that P3 amplitude is larger in individuals with higher WM in both n-back (Dong et al., 2015; Evans et al., 2011) and other memory tasks (Dunn et al., 1998; Shiran and Breznitz, 2011). Intriguingly, a similar increase of P3 amplitude by PHSs had been observed in a previous study (Zahedi et al., 2019), aiming to inhibit access to word meanings in a Stroop task. Therefore, it seems the effects of PHSs are mediated through the implementation of enhanced cognitive control of various kinds, a conclusion that may generalize beyond the updating function.

The second type of PHS effect on ERPs was observed in amplitude of the posterior old-new component, which decreased more strongly for the lower Load 2 than for the more difficult Load 3 condition. In Experiment 1 and in the NH condition of Experiment 2, we found a load effect only in the first segment of the posterior component but not in the later segment, possibly due to a ceiling effect for the second segment, as all materials were studied with maximum effort in both of these hard conditions (Vogel and Machizawa, 2004). However, in the PHS condition of Experiment 2, the amplitude of this component was diminished relative to the NH condition, particularly for Load 2. Therefore, the neurocognitive processes reflected in this ERP component may be related to a diminished pressure on memory processes, such as storing and retrieving information in WM buffers, due to the enhanced implementation of cognitive control mechanisms or resources. Therefore, this later effect might be seen as a consequence of earlier ones and may provide further support that PHS affects performance similarly to cognitive training, that is, by deploying more proactive control, which decreases the need employing reactive control.

This view is also in line with enhancements of WM in children by means of efficient and transfer-enabling training programs that correlate with changes in the neural networks involved in the task (Klingberg, 2010; Moreno et al., 2011; Rueda et al., 2005). Consequently, the present performance enhancements due to PHSs, going along with activity changes of the neural networks involved in the tone-monitoring task and the updating function, resonate with our suggestion that PHS works similar to an efficient training program, with one important difference: performance improvements by PHS appear to be achieved more rapidly than by cognitive training.

Do our results have any bearing for different perspectives on hypnosis, that is, for the state versus sociocognitive theory? Our results simply indicate that effects of hypnosis can be interpreted from a sociocognitive perspective without requiring any assumption about a special state of consciousness during hypnosis. In other words, the same mechanisms available in the normal waking state seem to be sufficient for explaining the effects of PHS on updating in WM and likely also for other EFs.

Since it is widely accepted that Stroop effects are resilient to practice (MacLeod, 1991), how can our account that PHS effects are similar to mental practice explain performance improvements due to PHSs in Stroop tasks? First, Stroop effects are resilient to practice but not immune. Many studies showed that Stroop effects can be significantly reduced by practice in participants of almost every age (e.g., Dulaney and Rogers, 1994; Protopapas et al., 2014). According to MacLeod (1991), Ridley Stroop was the first to report effects of practice, as he observed that after several days of extensive practice, the response of color detection became semi-automatic and there was even a reversed Stroop effect, that is, when the task was changed from detecting colors to reading words, the print colors interfered with word meanings. Interestingly, it has been argued that the mechanism underlying changes in Stroop effects due to practice is related to developing a new semi-automatic response of color detection, which can compete with the previously established automatic response of word reading. In other words, the effects of practice can be considered as top-down modulations. Considering that most Stroop studies using suggestions also showed that PHSs may reduce Stroop effects but usually do not eliminate them (e.g., Augustinova and Ferrand, 2012; Raz et al., 2005; Raz et al., 2006; Zahedi et al., 2019), effects of PHSs are comparable to practice effects.

One might argue, whether the mere repetition of the visual strategy in the form of PHSs might cause better understanding and adherence – whether other components of PHSs are present or not. The design of our study renders this option unlikely. As the order of sessions was counterbalanced, some participants had received PHS in the first session, and therefore, when participating in the NH condition, they should have a superior understanding of the visual-cognitive strategy. However, the absence of order effects in the analysis of performance shows that participants still performed better in the PHS condition in comparison to the NH condition. Furthermore, as the performance in the NH condition was comparable in quality with the first experiment, in respect to both behavioral and neuroimaging data, the possibility that participants were "holding back" in the NH condition can be ruled out as well.

We suggested that our results indicate that effects of PHSs are mediated by the enhanced utilization of cognitive control. Considering that some studies show high-hypnotizable participants to have worse

EFs in comparison to low-hypnotizables (for review please see Parris, 2017), does this contradict our conclusions? Our results show, regardless of baseline cognitive capabilities, PHS effects are mediated via top-down regulation and PHSs can enhance the updating function in a WM task by helping participants to efficiently implement a strategy. Hence, even if participants in the present study had lower EF capabilities, they obviously benefited from PHS. This is in line with the results of Lindelov et al. (2017), which indicate that participants with brain injuries also benefit from PHS and show enhancements in WM tasks.

Nevertheless, the relationship between cognitive capabilities and hypnotizability is complex. For instance, several well-conducted recent neurocognitive studies showed that in NH conditions, high-hypnotizables performed better in cognitive tasks when compared to low-hypnotizables, which was corroborated by the measured neuronal correlates (Kirenskaya et al., 2019; Srzich et al., 2019). In contrast, Khodaverdi-Khani and Laurence (2016) showed digit span performance in high-hypnotizables is inferior in comparison to low-hypnotizables, but there was no significant difference in an N-back task, revealing inconclusive findings with regard to WM performance. Intriguingly, Terhune et al. (2011) showed that probably the relation between hypnotizability and cognitive capabilities is more complicated, and mediating factors, such as dissociative tendencies, should be taken into account. It is very important to consider, as discussed by Lynn et al. (2019), that hypnotizability depends on several factors, including, willingness and openness. Thus, participants with higher cognitive capabilities might be unwilling to accept suggestions and therefore, show no effects, and participants with comparatively lower cognitive capabilities might be motivated to cooperate, and therefore, show bigger effects.

4.4. Limitations and perspectives

In the current study, we only recruited high-hypnotizable participants. As discussed by Jensen et al. (2017), it would be interesting to replicate the current study with medium-hypnotizable participants in order to enhance the generalizability of results.

Further, one might discuss that experimenters' intention can be a confound in the current study, as our PHS was explicitly about task performance. However, as reviewed by Lynn et al. (2019), willingness to be hypnotized is one of the determining factors in suggestibility of participants, which reveals why motivation and hypnosis effects are very hard to be separated. As Jones and Spanos (1982) have shown, low-suggestibles, whom the authors termed "negative subjects", might even try to counter the experimenters' intention. Therefore, using low-hypnotizable control groups, as it is prevalent in the field, may complicate the interpretability of results, and do not control for motivation as a confounding factor. In addition, we used a counterbalanced design, which was not disclosed to our participants, in order to prevent them from underperforming in the NH condition. Indeed, based on the similarity of results in the NH condition with the results of Experiment 1, the holding back hypothesis can be ruled out. That means, differences in performance were likely due to enhancements in proactive control in the PHS session rather than to holding back in the control session (NH session). Hence, even if our participants had tried to align themselves with experimenters' intentions, it does not refute the overall conclusion that PHS effects are mediated via top-down regulation. Finally, we tried to support our conclusions by comparing the alterations in ERP components due to PHS, with findings from cognitive training investigations. This, along with the relative robustness of ERP components against intentional modifications, strengthens our suggestion, that PHSs may act akin to mental imagery promoting mental practice.

Finally, we want to point out a general limitation with regard to ERP analyses. The time windows used for peak analyses and topographies of ERP components are usually somewhat variable across experiments. However, this is not surprising as the average head and brain shapes and processing speed can vary across samples, which may affect the ERP components' properties. Therefore, small variations in time windows of different peaks and topographical distributions are to be expected. From Experiment 1 to Experiment 2 and in line with the literature, we tried to use a homogenous time-window and ROIs; however, since wave shapes and topographies of some components showed slight variations, we adopted our time windows and ROIs accordingly if deemed necessary; noticeably, none of these differences were large-. In other words, even though the general timeframes for each component were established a priori, the exact time-windows had to be slightly adjusted according to variations in peaks and waveshapes of the recorded ERPs.

Future studies should directly compare PHS and training programs on relevant parameters such as efficiency, sustainability, transferability, and dependency on hypnotic suggestibility of the trainee. Although it is likely that the PHS used in our study was highly specific for the tone-monitoring task, we think, it is possible to develop instructions with a broader range of applications.

5. Conclusions

In conclusion, the present study showed that load effects in the tone-monitoring task consistently resemble effects previously reported in n-back and other memory tasks, ranging from increased attention dispersion, diminished predictability, and various memory processes; hence, our results provide converging evidence about the generalizability of ERP correlates of updating. More importantly, the current study shows that PHSs can affect the updating function, a pure top-down component of WM. The neurocognitive mechanisms inferred from ERPs revealed that PHSs affect behavior due to the proactive deployment of additional cognitive control, which subsequently diminishes pressure on WM buffers. Therefore, PHS can enhance performance by strengthening top-down regulation and our results strongly indicate that our PHS, consisting of imagery techniques, can be viewed as representing a special form of mental practice, helping participants to develop a context-dependent trigger-action contingency. Hence, these results offer a novel and promising perspective on enhancing WM by targeting the updating function. Given the challenges for developing efficient training programs to enhance WM, further research should explore the potentials and limitations of this approach.

CRediT author statement

Anoushiravan Zahedi, Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition, Birgit Stürmer, Supervision, Writing - review & editing, Werner Sommer, Supervision, Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Funding acquisition

Acknowledgment

For accessing the raw data, task, and supplementary materials of the experiments please see:

DOI: https://doi.org/10.17605/OSF.IO/PHBXS.

This research was supported by a scholarship to A.Z. by the German Academic Exchange Service (DAAD). We thank Sophie Dunn and Katja Zellner for help in data acquisition and Ulrike Bunzenthal, Rainer Kniesche, and Thomas Pinkpank for technical support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2020.107632.

References

Abdel Rahman, R., Sommer, W., 2008. Seeing what we know and understand: how knowledge shapes perception. Psychon. Bull. Rev. 15 (6), 1055–1063. https://doi.org/10.3758/PBR.15.6.1055.

Abrahamse, E.L., Verwey, W.B., 2008. Context dependent learning in the serial RT task. Psychol. Res. 72 (4), 397–404. https://doi.org/10.1007/s00426-007-0123-5.

Augustinova, M., Ferrand, L., 2012. Suggestion does not de-automatize word reading: evidence from the semantically based Stroop task. Psychon. Bull. Rev. 19 (3), 521–527. https://doi.org/10.3758/s13423-012-0217-y.

Baddeley, A., 2003. Working memory: looking back and looking forward. Nat. Rev. Neurosci. 4 (10), 829–839. https://doi.org/10.1038/nrn1201.

Berg, P., Scherg, M., 1991. Dipole models of eye movements and blinks. Electroencephalogr. Clin. Neurophysiol. 79 (1), 36–44.

Bongartz, W., 1985. German norms for the harvard group scale of hypnotic susceptibility, form A. IJCEH (Int. J. Clin. Exp. Hypn.) 33 (2), 131–139. https://doi.org/10.1080/00207148508406643.

Braver, T.S., 2012. The variable nature of cognitive control: a dual mechanisms framework. Trends Cognit. Sci. 16 (2), 106–113. https://doi.org/10.1016/j.tics.2011.12.010.

Braver, T.S., Paxton, J.L., Locke, H.S., Barch, D.M., 2009. Flexible neural mechanisms of cognitive control within human prefrontal cortex. Proceedings of the National Academy of Sciences of the United States of America 106 (18), 7351–7356. https://doi.org/10.1073/pnas.0808187106, 18.

Brouwer, A.M., Hogervorst, M.A., van Erp, J.B., Heffelaar, T., Zimmerman, P.H., Oostenveld, R., 2012. Estimating workload using EEG spectral power and ERPs in the n-back task. J. Neural. Eng. 9 (4) https://doi.org/10.1088/1741-2560/9/4/045008, 045008.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences. L. Erlbaum Associates, Hillsdale. New Jersey.

Cohen, J., 2016. Statistical power analysis. Curr. Dir. Psychol. Sci. 1 (3), 98–101. https://doi.org/10.1111/1467-8721.ep10768783.

Cooper, R., Shallice, T., 2000. Contention scheduling and the control of routine activities. Cogn. Neuropsychol. 17 (4), 297–338. https://doi.org/10.1080/026432900380427.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J. Neurosci. Methods 134 (1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009.

Diamond, A., 2013. Executive functions. Annu. Rev. Psychol. 64, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750.

Diamond, A., Ling, D.S., 2016. Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. Dev. Cogn. Neuro.-Neth. 18, 34–48. https://doi.org/10.1016/j.dcn.2015.11.005.

Donchin, E., Coles, M.G.H., 1988. Is the P300 component a manifestation of context updating? Behav. Brain Sci. 11 (3), 357–374. https://doi.org/10.1017/s0140525x00058027.

Dong, S., Reder, L.M., Yao, Y., Liu, Y., Chen, F., 2015. Individual differences in working memory capacity are reflected in different ERP and EEG patterns to task difficulty. Brain Res. 1616, 146–156. https://doi.org/10.1016/j.brainres.2015.05.003.

Dulaney, C.L., Rogers, W.A., 1994. Mechanisms underlying reduction in Stroop interference with practice for young and old adults. J. Exp. Psychol. Learn. Mem. Cognit. 20 (2), 470–484. https://doi.org/10.1037//0278-7393.20.2.470.

Dunn, B.R., Dunn, D.A., Languis, M., Andrews, D., 1998. The relation of ERP components to complex memory processing. Brain Cognit. 36 (3), 355–376.

Eden, G.F., VanMeter, J.W., Rumsey, J.M., Maisog, J.M., Woods, R.P., Zeffiro, T.A., 1996. Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. Nature 382 (6586), 66–69. https://doi.org/10.1038/382066a0.

Egner, T., Jamieson, G., Gruzelier, J., 2005. Hypnosis decouples cognitive control from conflict monitoring processes of the frontal lobe. Neuroimage 27 (4), 969–978. https://doi.org/10.1016/j.neuroimage.2005.05.002.

Egner, T., Raz, A., 2007. Cognitive control Processes and Hypnosis. In Jamieson, A. (Ed.), Hypnosis and conscious States: The Cognitive Neuroscience Perspective,. Oxford University Press, Oxford, pp. 29–50.

Elkins, G.R., Barabasz, A.F., Council, J.R., Spiegel, D., 2015. Advancing research and practice: the revised APA Division 30 definition of hypnosis. Am. J. Clin. Hypn. 57 (4), 378–385. https://doi.org/10.1080/00029157.2015.1011465.

Ester, E.F., Sprague, T.C., Serences, J.T., 2015. Parietal and frontal cortex encode stimulus-specific mnemonic representations during visual working memory. Neuron 87 (4), 893–905. https://doi.org/10.1016/j.neuron.2015.07.013.

Evans, J.L., Selinger, C., Pollak, S.D., 2011. P300 as a measure of processing capacity in auditory and visual domains in specific language impairment. Brain Res. 1389, 93–102. https://doi.org/10.1016/j.brainres.2011.02.010.

Faul, F., Erdfelder, E., Lang, A.G., Buchner, A., 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav. Res. Methods 39 (2), 175–191. https://doi.org/10.3758/bf03193146.

Folstein, J.R., Van Petten, C., 2008. Influence of cognitive control and mismatch on the N2 component of the ERP: a review. Psychophysiology 45 (1), 152–170. https://doi.org/10.1111/j.1469-8986.2007.00602.x.

Frank, C., Land, W.M., Schack, T., 2015. Perceptual-cognitive changes during motor learning: the influence of mental and physical practice on mental representation, gaze behavior, and performance of a complex action. Front. Psychol. 6, 1981. https://doi.org/10.3389/fpsyg.2015.01981.

Frank, T.D., 2016. Perception adapts via top-down regulation to task repetition: a Lotka-Volterra-Haken modeling analysis of experimental data. J. Integr. Neurosci. 15 (1), 67–79. https://doi.org/10.1142/S0219635216500059.

Frtusova, J.B., Winneke, A.H., Phillips, N.A., 2013. ERP evidence that auditory-visual speech facilitates working memory in younger and older adults. Psychol. Aging 28 (2), 481–494. https://doi.org/10.1037/a0031243.

Galea, V., Woody, E.Z., Szechtman, H., Pierrynowski, M.R., 2010. Motion in response to the hypnotic suggestion of arm rigidity: a window on underlying mechanisms. IJCEH (Int. J. Clin. Exp. Hypn.) 58 (3), 251–268. https://doi.org/10.1080/00207141003760561.

Gobel, E.W., Parrish, T.B., Reber, P.J., 2011. Neural correlates of skill acquisition: decreased cortical activity during a serial interception sequence learning task. Neuroimage 58 (4), 1150–1157. https://doi.org/10.1016/j.neuroimage.2011.06.090.

Green, J.P., Lynn, S.J., 2011. Hypnotic responsiveness: expectancy, attitudes, fantasy proneness, absorption, and gender. IJCEH (Int. J. Clin. Exp. Hypn.) 59 (1), 103–121. https://doi.org/10.1080/00207144.2011.522914.

Hammond, D.C., 1990. Handbook of Hypnotic Suggestions and Metaphors. WW Norton & Company, New York.

Hammond, D.C., 1998. Hypnotic Induction and Suggestion. American Society of Clinical Hypnosis, Chicago, IL.

Han, L., Liu, Y., Zhang, D., Jin, Y., Luo, Y., 2013. Low-arousal speech noise improves performance in N-back task: an ERP study. PloS One 8 (10). https://doi.org/10.1371/journal.pone.0076261 e76261.

Hesslow, G., 2002. Conscious thought as simulation of behaviour and perception. Trends Cognit. Sci. 6 (6), 242–247. https://doi.org/10.1016/s1364-6613(02)01913-7.

Hill, B.D., Elliott, E.M., Shelton, J.T., Pella, R.D., O'Jile, J.R., Gouvier, W.D., 2010. Can we improve the clinical assessment of working memory? An evaluation of the Wechsler Adult Intelligence Scale-Third Edition using a working memory criterion construct. J. Clin. Exp. Neuropsychol. 32 (3), 315–323. https://doi.org/10.1080/13803390903032529.

Hillyard, S.A., Anllo-Vento, L., 1998. Event-related brain potentials in the study of visual selective attention. Proceedings of the National Academy of Sciences of the United States of America 95 (3), 781–787. https://doi.org/10.1073/pnas.95.3.781, 3.

Hoechstetter, K., Bornfleth, H., Weckesser, D., Ille, N., Berg, P., Scherg, M., 2004. BESA source coherence: a new method to study cortical oscillatory coupling. Brain Topogr. 16 (4), 233–238.

Huster, R.J., Enriquez-Geppert, S., Lavallee, C.F., Falkenstein, M., Herrmann, C.S., 2013. Electroencephalography of response inhibition tasks: functional networks and cognitive contributions. Int. J. Psychophysiol. 87 (3), 217–233. https://doi.org/10.1016/j.ijpsycho.2012.08.001.

Iani, C., Ricci, F., Baroni, G., Rubichi, S., 2009. Attention control and susceptibility to hypnosis. Conscious. Cognit. 18 (4), 856–863. https://doi.org/10.1016/j.concog.2009.07.002.

Iani, C., Ricci, F., Gherri, E., Rubichi, S., 2006. Hypnotic suggestion modulates cognitive conflict: the case of the flanker compatibility effect. Psychol. Sci. 17 (8), 721–727. https://doi.org/10.1111/j.1467-9280.2006.01772.x.

Jensen, M.P., Jamieson, G.A., Lutz, A., Mazzoni, G., McGeown, W.J., Santarcangelo, E.L., Terhune, D.B., 2017. New directions in hypnosis research: strategies for advancing the cognitive and clinical neuroscience of hypnosis. Neurosci Conscious 3 (1). https://doi.org/10.1093/nc/nix004.

Jones, B., Spanos, N.P., 1982. Suggestions for altered auditory sensitivity, the negative subject effect and hypnotic susceptibility: a signal detection analysis. J. Pers. Soc. Psychol. 43 (3), 637–647. https://doi.org/10.1037/0022-3514.43.3.637.

Khodaverdi-Khani, M., Laurence, J.-R., 2016. Working Memory and Hypnotizability. Psychology of Consciousness: Theory, Research, and Practice 3 (1), 80–92. https://doi.org/10.1037/cns0000058, 1.

Kihlstrom, J.F., 1985. Hypnosis. Annu. Rev. Psychol. 36, 385–418. https://doi.org/10.1146/annurev.ps.36.020185.002125.

Kirenskaya, A.V., Storozheva, Z.I., Solntseva, S.V., Novototsky-Vlasov, V.Y., Gordeev, M. N., 2019. Auditory evoked potentials evidence for differences in information processing between high and low hypnotizable subjects. IJCEH (Int. J. Clin. Exp. Hypn.) 67 (1), 81–103. https://doi.org/10.1080/00207144.2019.1553764.

Klingberg, T., 2010. Training and plasticity of working memory. Trends Cognit. Sci. 14 (7), 317–324. https://doi.org/10.1016/j.tics.2010.05.002.

Kreidler, S.M., Muller, K.E., Grunwald, G.K., Ringham, B.M., Coker-Dukowitz, Z.T., Sakhadeo, U.R., Glueck, D.H., 2013. GLIMMPSE: online power computation for linear models with and without a baseline covariate. J. Stat. Software 54 (10). https://doi.org/10.18637/jss.v054.i10.

Li, W., Guo, Z., Jones, J.A., Huang, X., Chen, X., Liu, P., Liu, H., 2015. Training of working memory impacts neural processing of vocal pitch regulation. Sci. Rep. 5 https://doi.org/10.1038/srep16562, 16562.

Lifshitz, M., Aubert Bonn, N., Fischer, A., Kashem, I.F., Raz, A., 2013. Using suggestion to modulate automatic processes: from Stroop to McGurk and beyond. Cortex 49 (2), 463–473. https://doi.org/10.1016/j.cortex.2012.08.007.

Lindelov, J.K., Overgaard, R., Overgaard, M., 2017. Improving working memory performance in brain-injured patients using hypnotic suggestion. Brain 140 (4), 1100–1106. https://doi.org/10.1093/brain/awx001.

Lobier, M.A., Peyrin, C., Pichat, C., Le Bas, J.F., Valdois, S., 2014. Visual processing of multiple elements in the dyslexic brain: evidence for a superior parietal dysfunction. Front. Hum. Neurosci. 8, 479. https://doi.org/10.3389/fnhum.2014.00479.

Lynn, S.J., Green, J.P., 2011. The sociocognitive and dissociation theories of hypnosis: toward a rapprochement. IJCEH (Int. J. Clin. Exp. Hypn.) 59 (3), 277–293. https://doi.org/10.1080/00207144.2011.570652.

Lynn, S.J., Green, J.P., Kirsch, I., Capafons, A., Lilienfeld, S.O., Laurence, J.R., Montgomery, G.H., 2015. Grounding hypnosis in science: the "new" APA division 30 definition of hypnosis as a step backward. Am. J. Clin. Hypn. 57 (4), 390–401. https://doi.org/10.1080/00029157.2015.1011472.

Lynn, S.J., Green, J.P., Polizzi, C.P., Ellenberg, S., Gautam, A., Aksen, D., 2019. Hypnosis, hypnotic phenomena, and hypnotic responsiveness: clinical and research foundations-A 40-year perspective. IJCEH (Int. J. Clin. Exp. Hypn.) 67 (4), 475–511. https://doi.org/10.1080/00207144.2019.1649541.

MacLeod, C.M., 1991. Half a century of research on the Stroop effect: an integrative review. Psychol. Bull. 109 (2), 163–203. https://doi.org/10.1037/0033-2909.109.2.163.

Manita, S., Suzuki, T., Homma, C., Matsumoto, T., Odagawa, M., Yamada, K., Murayama, M., 2015. A top-down cortical circuit for accurate sensory perception. Neuron 86 (5), 1304–1316. https://doi.org/10.1016/j.neuron.2015.05.006.

McConkey, K.M., Sheehan, P.W., Law, H.G., 1980. Structural analysis of the harvard group scale of hypnotic susceptibility, form A. IJCEH (Int. J. Clin. Exp. Hypn.) 28 (2), 164–175. https://doi.org/10.1080/00207148008409838.

Melby-Lervag, M., Hulme, C., 2016. There is no convincing evidence that working memory training is effective: a reply to Au et al. (2014) and Karbach and Verhaeghen (2014). Psychon. Bull. Rev. 23 (1), 324–330. https://doi.org/10.3758/s13423-015-0862-z.

Melby-Lervag, M., Redick, T.S., Hulme, C., 2016. Working memory training does not improve performance on measures of intelligence or other measures of "ar transfer": evidence from a meta-analytic review. Perspect. Psychol. Sci. 11 (4), 512–534. https://doi.org/10.1177/1745691616635612.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., Wager, T.D., 2000. The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. Cognit. Psychol. 41 (1), 49–100. https://doi.org/10.1006/cogp.1999.0734.

Moreno, S., Bialystok, E., Barac, R., Schellenberg, E.G., Cepeda, N.J., Chau, T., 2011. Short-term music training enhances verbal intelligence and executive function. Psychol. Sci. 22 (11), 1425–1433. https://doi.org/10.1177/0956797611416999.

Nakao, Y., Kodabashi, A., Yarita, M., Fujimoto, T., Tamura, T., 2012. Temporal activities during P3 components on the working memory-related brain regions: N-back ERP study. In: Paper Presented at the Proceedings of 2012 IEEE-EMBS International Conference on Biomedical and Health Informatics.

Nemeth, D., Janacsek, K., Polner, B., Kovacs, Z.A., 2013. Boosting human learning by hypnosis. Cerebr. Cortex 23 (4), 801–805. https://doi.org/10.1093/cercor/bhs068.

Norman, D.A., Shallice, T., 1986. Attention to action. In Davidson, R. J., Schwartz, G. E., Shapiro, D. (Eds.), Consciousness and Self-Regulation, Advances in Research and Theory Volume 4. Springer, Boston, pp. 1–18.

Parris, B.A., 2017. The role of frontal executive functions in hypnosis and hypnotic suggestibility. Psychology of Consciousness: Theory, Research, and Practice 4 (2), 211–229. https://doi.org/10.1037/cns0000106.

Parris, B.A., Dienes, Z., 2013. Hypnotic suggestibility predicts the magnitude of the imaginative word blindness suggestion effect in a non-hypnotic context. Conscious. Cognit. 22 (3), 868–874. https://doi.org/10.1016/j.concog.2013.05.009.

Parris, B.A., Dienes, Z., Hodgson, T.L., 2012. Temporal constraints of the word blindness posthypnotic suggestion on Stroop task performance. J. Exp. Psychol. Hum. Percept. Perform. 38 (4), 833–837. https://doi.org/10.1037/a0028131.

Piccione, C., Hilgard, E.R., Zimbardo, P.G., 1989. On the degree of stability of measured hypnotizability over a 25-year period. J. Pers. Soc. Psychol. 56 (2), 289–295.

Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. Clin. Neurophysiol. 118 (10), 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019.

Protopapas, A., Vlahou, E.L., Moirou, D., Ziaka, L., 2014. Word reading practice reduces Stroop interference in children. Acta Psychol. 148, 204–208. https://doi.org/10.1016/j.actpsy.2014.02.006.

Raz, A., 2005. Attention and hypnosis: neural substrates and genetic associations of two converging processes. IJCEH (Int. J. Clin. Exp. Hypn.) 53 (3), 237–258. https://doi.org/10.1080/00207140590961295.

Raz, A., Fan, J., Posner, M.I., 2005. Hypnotic suggestion reduces conflict in the human brain. Proceedings of the National Academy of Sciences of the United States of America 102 (28), 9978–9983. https://doi.org/10.1073/pnas.0503064102, 28.

Raz, A., Kirsch, I., Pollard, J., Nitkin-Kaner, Y., 2006. Suggestion reduces the stroop effect. Psychol. Sci. 17 (2), 91–95. https://doi.org/10.1111/j.1467-9280.2006.01669.x.

Raz, A., Landzberg, K.S., Schweizer, H.R., Zephrani, Z.R., Shapiro, T., Fan, J., Posner, M. I., 2003. Posthypnotic suggestion and the modulation of Stroop interference under cycloplegia. Conscious. Cognit. 12 (3), 332–346. https://doi.org/10.1016/s1053-8100(03)00024-2.

Raz, A., Shapiro, T., 2002. Hypnosis and neuroscience: a cross talk between clinical and cognitive research. Arch. Gen. Psychiatr. 59 (1), 85–90. https://doi.org/10.1001/archpsyc.59.1.85.

Reinhart, R.M.G., Nguyen, J.A., 2019. Working memory revived in older adults by synchronizing rhythmic brain circuits. Nat. Neurosci. 22 (5), 820–827. https://doi.org/10.1038/s41593-019-0371-x.

Rudebeck, P.H., Putnam, P.T., Daniels, T.E., Yang, T., Mitz, A.R., Rhodes, S.E., Murray, E. A., 2014. A role for primate subgenual cingulate cortex in sustaining autonomic arousal. Proceedings of the National Academy of Sciences of the United States of America 111 (14), 5391–5396. https://doi.org/10.1073/pnas.1317695111, 14.

Rueda, M.R., Rothbart, M.K., McCandliss, B.D., Saccomanno, L., Posner, M.I., 2005. Training, maturation, and genetic influences on the development of executive attention. Proceedings of the National Academy of Sciences of the United States of America 102 (41), 14931–14936. https://doi.org/10.1073/pnas.0506897102, 41.

Rugg, M.D., Curran, T., 2007. Event-related potentials and recognition memory. Trends Cognit. Sci. 11 (6), 251–257. https://doi.org/10.1016/j.tics.2007.04.004.

Rugg, M.D., Yonelinas, A.P., 2003. Human recognition memory: a cognitive neuroscience perspective. Trends Cognit. Sci. 7 (7), 313–319. https://doi.org/10.1016/s1364-6613(03)00131-1.

Ruitenberg, M.F., De Kleine, E., Van der Lubbe, R.H., Verwey, W.B., Abrahamse, E.L., 2012. Context-dependent motor skill and the role of practice. Psychol. Res. 76 (6), 812–820. https://doi.org/10.1007/s00426-011-0388-6.

Saalmann, Y.B., Kastner, S., 2009. Gain control in the visual thalamus during perception and cognition. Curr. Opin. Neurobiol. 19 (4), 408–414. https://doi.org/10.1016/j.conb.2009.05.007.

Scharinger, C., Soutschek, A., Schubert, T., Gerjets, P., 2017. Comparison of the working memory load in n-back and working memory span tasks by means of EEG frequency band power and p300 amplitude. Front. Hum. Neurosci. 11, 6. https://doi.org/10.3389/fnhum.2017.00006.

Schmiedek, F., Hildebrandt, A., Lovden, M., Wilhelm, O., Lindenberger, U., 2009. Complex span versus updating tasks of working memory: the gap is not that deep. J. Exp. Psychol. Learn. Mem. Cognit. 35 (4), 1089–1096. https://doi.org/10.1037/a0015730.

Sheehan, P.W., Donovan, P., MacLeod, C.M., 1988. Strategy manipulation and the Stroop effect in hypnosis. J. Abnorm. Psychol. 97 (4), 455–460. https://doi.org/10.1037/0021-843x.97.4.455.

Shiran, A., Breznitz, Z., 2011. The effect of cognitive training on recall range and speed of information processing in the working memory of dyslexic and skilled readers. J. Neurolinguistics 24 (5), 524–537. https://doi.org/10.1016/j.jneuroling.2010.12.001.

Shor, R.E., Orne, E.C., 1962. Harvard Group Scale of Hypnotic Susceptibility. Consulting Psychologists Press, Palo Alto.

Srzich, A.J., Cirillo, J., Stinear, J.W., Coxon, J.P., McMorland, A.J.C., Anson, J.G., 2019. Does hypnotic susceptibility influence information processing speed and motor cortical preparatory activity? Neuropsychologia 129, 179–190. https://doi.org/10.1016/j.neuropsychologia.2019.03.014.

Stefanidis, D., Anton, N.E., Howley, L.D., Bean, E., Yurco, A., Pimentel, M.E., Davis, C.K., 2017. Effectiveness of a comprehensive mental skills curriculum in enhancing surgical performance: results of a randomized controlled trial. Am. J. Surg. 213 (2), 318–324. https://doi.org/10.1016/j.amjsurg.2016.10.016.

Terhune, D.B., Cardena, E., Lindgren, M., 2011. Dissociative tendencies and individual differences in high hypnotic suggestibility. Cognit. Neuropsychiatry 16 (2), 113–135. https://doi.org/10.1080/13546805.2010.503048.

Terhune, D.B., Cleeremans, A., Raz, A., Lynn, S.J., 2017. Hypnosis and top-down regulation of consciousness. Neurosci. Biobehav. Rev. 81 (Pt A), 59–74. https://doi.org/10.1016/j.neubiorev.2017.02.002.

Thorell, L.B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., Klingberg, T., 2009. Training and transfer effects of executive functions in preschool children. Dev. Sci. 12 (1), 106–113. https://doi.org/10.1111/j.1467-7687.2008.00745.x.

Tobis, I.P., Kihlstrom, J.F., 2010. Allocation of attentional resources in posthypnotic suggestion. IJCEH (Int. J. Clin. Exp. Hypn.) 58 (4), 367–382. https://doi.org/10.1080/00207144.2010.499330.

van der Graaf, F.H., Maguire, R.P., Leenders, K.L., de Jong, B.M., 2006. Cerebral activation related to implicit sequence learning in a Double Serial Reaction Time task. Brain Res. 1081 (1), 179–190. https://doi.org/10.1016/j.brainres.2006.01.103.

Vogel, E.K., Machizawa, M.G., 2004. Neural activity predicts individual differences in visual working memory capacity. Nature 428 (6984), 748–751. https://doi.org/10.1038/nature02447.

Warrington, E.K., Shallice, T., 1980. Word-form dyslexia. Brain 103 (1), 99–112. https://doi.org/10.1093/brain/103.1.99.

Watter, S., Geffen, G.M., Geffen, L.B., 2001. The n-back as a dual-task: P300 morphology under divided attention. Psychophysiology 38 (6), 998–1003.

Wilding, E.L., Ranganath, C., 2011. Electrophysiological correlates of episodic memory processes. In: In Luck, S. J., Kappenman, E. S. (Eds.), The Oxford Handbook of Event-Related Potential Components. Oxford University Press, Oxford, pp. 373–396.

Wilhelm, O., Hildebrandt, A., Oberauer, K., 2013. What is working memory capacity, and how can we measure it? Front. Psychol. 4 https://doi.org/10.3389/fpsyg.2013.00433, 433.

Zahedi, A., Abdel Rahman, R., Sturmer, B., Sommer, W., 2019. Common and specific loci of Stroop effects in vocal and manual tasks, revealed by event-related brain potentials and posthypnotic suggestions. J. Exp. Psychol. Gen. 148 (9), 1575–1594. https://doi.org/10.1037/xge0000574.

Zahedi, A., Luczak, A., Sommer, W., 2020. Modification of Food Preferences by Posthypnotic Suggestions: an Event-Related Brain Potential Study. Appetite. https://doi.org/10.1016/j.appet.2020.104713, 104713.

Zahedi, A., Stuermer, B., Hatami, J., Rostami, R., Sommer, W., 2017. Eliminating stroop effects with post-hypnotic instructions: brain mechanisms inferred from EEG. Neuropsychologia. https://doi.org/10.1016/j.neuropsychologia.2017.01.006.

How hypnotic suggestions work – critical review of prominent theories and a novel synthesis

Anoushiravan Zahedi*, Werner Sommer

Humboldt Universität zu Berlin

Author Note

* Corresponding Author; Institut für Psychologie, Humboldt-Universität zu, Rudower Chaussee 18, 12489, Berlin, Germany.

E-mail address: zahedian@hu-berlin.de

Abstract

Hypnotic and posthypnotic suggestions are frequently and successfully implemented in behavioral, neurocognitive, and clinical investigations and interventions. Despite abundant reports about the effectiveness of suggestions in altering behavior, perception, cognition, and subjective sense of agency (SoA), there is no consensus about the neurocognitive mechanisms driving these changes. The present review starts with procedural descriptions of hypnosis, suggestions, and suggestibility, followed by a systematic and comparative review of prominent theories of hypnosis, highlighting their strengths and weaknesses, based on their power to explain existing observations in the domain of hypnosis. Thereafter, we propose a novel theory of hypnosis, accounting for empirical evidence and synthesizing concepts from hypnosis and neurocognitive theories. The proposed simulation-adaption theory of hypnosis (SATH) is founded on three elements: cognitive-simulation, top-down sensory-adaptation, and mental training. SATH mechanistically explains different hypnotic phenomena, such as alterations in the SoA, positive and negative hallucinations, motor suggestions, and effects of suggestions on executive functions and memory. Finally, based on SATH and its postulated neurocognitive mechanisms, a procedure-oriented definition of hypnosis is proposed.

Keywords: Cognitive Control, Sense of Agency, Hypnotic Suggestions (HS), Posthypnotic Suggestions (PHS), Hypnosis, Suggestibility, Hypnotizability, Cognitive Simulation, Top-Down Sensory Adaption, Predictive Coding Model, Mental Practice, Imagination, Executive Functions.

Table of contents

How hypnotic suggestions work – critical review of prominent theories and a novel synthesis

1. Introduction

Hypnosis is an effective intervention used in clinical settings, among others for treating depression (e.g., Alladin & Alibhai, 2007), anxiety-related disorders (e.g., Valentine, Milling, Clark, & Moriarty, 2019), acute and chronic pain (Thompson et al., 2019), obesity and overweight (Kirsch, 1996; Milling, Gover, & Moriarty, 2018), for enhancing self-acceptance (e.g., Milburn, 2010), and as an adjunct to cognitive-behavior therapy (e.g., Schoenberger, 2000). In basic psychological research, hypnotic and posthypnotic suggestions are frequently employed to investigate psychological functions and their neurocognitive mechanisms, among others for enhancing inhibition (e.g., Augustinova & Ferrand, 2012; Iani, Ricci, Gherri, & Rubichi, 2006; Raz, Kirsch, Pollard, & Nitkin-Kaner, 2006; Zahedi, Abdel Rahman, Sturmer, & Sommer, 2019; Zahedi, Stuermer, Hatami, Rostami, & Sommer, 2017), boosting working memory (e.g., Lindelov, Overgaard, & Overgaard, 2017; Zahedi, Sturmer, & Sommer, 2020), modifying perception (e.g., Derbyshire, Whalley, Stenger, & Oakley, 2004; McGeown et al., 2012; Perri, Rossani, & Di Russo, 2019), and altering implicit motivation (e.g., Ludwig et al., 2014; Zahedi, Luczak, & Sommer, 2020). According to these reports, hypnosis is an established procedure with proven efficacy. However, there is no consensus about the mechanisms underlying the effects of hypnosis and hypnotic suggestions. What is common to the phenomena subsumed under the name of hypnosis and why it is effective in changing such diverse functions as behavior, perception, cognition, and the subjective sense of agency (SoA)? We begin our review by describing the procedures of hypnosis, discuss individual differences in responding to suggestions, and address the possible changes in psychological functions caused by hypnotic and posthypnotic suggestions. Then, we will review the most prominent accounts of hypnosis and discuss their strengths and shortcomings in explaining the observed effects in the literature. Finally, we will introduce a new theoretical framework, which offers a broader explanatory framework and better predictive power in comparison to existing theories.

1.1. Hypnosis

The procedure of hypnosis commonly consists of three semi-distinguishable stages (Hammond, 1998; Kihlstrom, 2008), namely, induction, deepening (including hypnotic and posthypnotic suggestions), and termination. All three stages are induced in a participant by another person, called the hypnotist, who presents suitable suggestions (Kihlstrom, 1985; Lynn, Green, et al., 2015; Lynn, Laurence, & Kirsch, 2015). The term "suggestion" indicates that participants are going to experience intentional responses, and can be distinguished from "instruction" or "command" that allude to nonvoluntary acts (Kirsch, 1999). For hypnotic inductions, innumerable different suggestions can be used (Hammond, 1998), and there is a long debate about their importance and role (Terhune & Cardena, 2016). However, most inductions share some basic characteristics. Two aims are commonly attributed to induction-related suggestions, firstly, to establish some basic expectancies about the procedure, which assumingly increases the responsiveness of the participants (Braffman & Kirsch, 1999). For instance, the word "hypnosis" will cue participants that their experience of the current situation may vastly differ from usual conditions and make them more responsive to future suggestions (Gandhi & Oakley, 2005). Secondly, induction aims to attract participants' attention and cause absorption in the suggestions presented by the hypnotist and in their own thoughts and feelings and, consequentially, being less attentive to their surroundings (Brown, Antonova, Langley, & Oakley, 2001), further consolidating adherence to the new expectancies. However, there is abundant evidence that hypnotic induction might actually have no effect on the responsiveness of participants to suggestions (Mazzoni et al., 2009; McGeown et al., 2012), may not be necessary for the effectiveness of suggestions (Parris & Dienes, 2013), and even in those cases where they enhance responsiveness, their effects are usually small in comparison to other predictors of responsiveness, such as suggestibility outside of hypnosis, imagination, or absorption capabilities (Braffman & Kirsch, 1999; Lynn, Laurence, et al., 2015). Hence, although part of the standard hypnotic procedure, the contribution of the induction phase to the efficacy of hypnotic suggestions are contested.

If hypnotic induction is followed by deepening, more suggestions will be presented to participants, which may try to relax participants or to achieve the same aims as induction-related suggestions. Alternatively, suggestions during deepening may be directed toward a targeted change in overt behavior, perception, or cognition. Throughout the remaining article, we refer to these targeted suggestions when discussing hypnotic and posthypnotic suggestions and their effects, especially in sections ***1.2. Objective Changes in Overt Behavior, Perception, and Cognition***, and ***1.3. Alterations in the Subjective*** Sense of A.

Finally, a suggestion at the end of hypnosis will usually cue the termination of the hypnotic procedure. Again, as for induction-related suggestions, there are a plethora of commonly used suggestions for hypnotic termination, but all have similar goals. That is, aiming to unwind the effects of hypnotic induction, these instructions direct attention to the surroundings and reestablish the normal expectancies about the effects of one's own behavior and perception of external stimuli (Hammond, 1998; Shor & Orne, 1962).

According to Kihlstrom (2008), the domain of hypnosis consists of any effect that suggestions – including those given during induction, deepening, or termination periods – have on hypnotized participants. Thus, the domain of hypnosis incorporates, firstly, objective and measurable changes in overt behavior, perception, and cognition and, secondly, alterations in the subjective SoA or the sense of conviction. In the two following sections, we will briefly review the objective and subjective effects of suggestions.

1.2. Objective Changes in Overt Behavior, Perception, and Cognition

Most commonly, hypnotic and posthypnotic suggestions *trigger well-learned or well-known responses.* These responses can be physical movements triggered by the suggestion to think of a movement, such as the ideomotor suggestions of the Harvard group-scale of hypnotic susceptibility (HGSHS; Shor & Orne, 1962). For instance, the suggestion “think of your head falling forward … and you feel a tendency to make the movement” (Shor & Orne, 1962; p.p. 4), typically causes participants’ head to drop forward. Physical movements can also be triggered by the suggestion to imagine a well-known stimulus, for instance, the suggestion “your hand starts to feel heavy… imagine that a weight is pulling it down… as it feels heavy it begins to move“ (Shor & Orne, 1962; p.p. 7), often leads to dropping one’s hand.

Suggestion-triggered responses can also be physiological reactions induced by the imagination of a well-known stimulus; for example, when participants are asked to imagine the sourness of a lemon, saliva secretion may be triggered (Hammond, 1990, 1998). Notably, the secretion of saliva here is a response to a conditioned stimulus (imagined lemon taste) rather than an unconditioned stimulus (real lemon taste). Suggestion-induced well-known responses may also be a change in perception without any overt action. Notably, here we refer to these responses as well-known responses, to emphasize that participants can only imagine stimuli, which they had been previously exposed to several times and, hence, are well-acquainted with them (these items may not only be physical entities but also abstract concepts, such as angels). In the hypnosis nomenclature, these changes in perception are commonly designated as hallucinations; positive hallucinations designate perceiving previously encountered stimulus in their absence, and negative hallucinations refer to the complete, partial, or temporary agnosia of stimuli that are in fact present. A common example of positive hallucinations is a color hallucination, for example, when hypnotized participants see a gray scale in different colors when suggested to do so (Mazzoni et al., 2009; McGeown et al., 2012). An example of negative hallucinations is the hypnosis-induced elimination or reduction of pain, inflicted by noxious stimuli (e.g., Perri et al., 2020; Perri et al., 2019; for review please see Thompson et al., 2019). Noteworthy, we categorized these responses as objective, as these suggestion-induced changes in perceptions can be objectively measured, for instance by implicit tasks or neuroimaging.

Hypnotic and posthypnotic suggestions can also affect cognitive functions (for review please see Kihlstrom, 2014; Lifshitz, Aubert Bonn, Fischer, Kashem, & Raz, 2013), that is, they can *modify responses to external stimuli*, *substitute* habitual responses with new responses that are more appropriate for the task at hand, or facilitate *learning and generation of new responses*. These cognitive functions are considered top-down processes and are often referred to as executive functions (EF; Baddeley, 2003; Diamond, 2013; Miyake et al., 2000). Even though there are different proposed taxonomies of EFs (Diamond, 2013; Miyake et al., 2000), two EFs are considered to be pivotal: (1) updating (sometimes called working memory), that is, storing, retrieving, and substituting information in working memory buffers, and (2) inhibition, that is, suppressing prepotent but task-inappropriate actions (Diamond, 2013; Miyake et al., 2000). Many studies have shown that task-relevant hypnotic and posthypnotic suggestions can enhance performance in both inhibition (e.g., Augustinova & Ferrand, 2012; Iani, Ricci, Baroni, & Rubichi, 2009; Iani et al., 2006; Raz, Fan, & Posner, 2005; Raz et al., 2006; Zahedi et al., 2019; Zahedi, Luczak, et al., 2020; Zahedi et al., 2017) and updating tasks (e.g., Lindelov et al., 2017; Zahedi, Sturmer, et al., 2020).

Considerably, despite some evidence that hypnosis without task-relevant hypnotic or posthypnotic suggestions (sometimes referred to as neutral hypnosis) may negatively affect performance in tasks challenging executive functions (Sheehan, Donovan, & MacLeod, 1988), other studies found no effect (Egner, Jamieson, & Gruzelier, 2005; Zahedi et al., 2017), or even improvements, for example, in implicit serial reaction-time tasks (Nemeth, Janacsek, Polner, & Kovacs, 2013).

Finally, hypnotic and posthypnotic suggestions can also affect long-term memory (Kihlstrom, 2014). More precisely, posthypnotic suggestions have been used to induce amnesia (i.e., posthypnotic amnesia). This amnesia affected episodic rather than semantic memory (e.g., Kihlstrom, 1980), lending credibility to claims that posthypnotic amnesia is related to amnesia for the source of knowledge (i.e., source amnesia). Further, it has been shown that posthypnotic amnesia is related to modulations of explicit but not implicit memory (Barnier, Bryant, & Briscoe, 2001; Bryant, Barnier, Mallard, & Tibbits, 1999; David, Brown, Pojoga, & David, 2000).

1.3. Alterations in the Subjective Sense of Agency

Numerous reviews and theoretical treatises regarding hypnosis put alterations in the SoA to the forefront of their discussions (e.g., Hilgard, 1973; Kihlstrom, 2008; Lynn, Laurence, et al., 2015; Martin & Pacherie, 2019; Terhune, Cleeremans, Raz, & Lynn, 2017). The reason for this emphasis is, it is very common that participants report a sense of semi-automaticity, effortlessness, and involuntariness, when they exert hypnotic-suggestion-induced responses (Blakemore, Oakley, & Frith, 2003; Kirsch & Lynn, 1997; Lynn, Rhue, & Weekes, 1990). However, as discussed by Lynn et al. (1990) the experience of involuntariness does not imply a loss of control over exerted responses. If appropriately encouraged, participants are able to resist hypnotic-suggestion-induced responses (Lynn, Nash, Rhue, Frauman, & Sweeney, 1984; Spanos, Cobb, & Gorassini, 1985).

Further, hypnotic-suggestion-induced responses are not automatic, since it is shown that they are resource-consuming (e.g., Tobis & Kihlstrom, 2010) and executed through the utilization of cognitive top-down processes (e.g., Zahedi, Sturmer, et al., 2020). Therefore, alterations in the SoA during hypnosis may be better explained as responses that are not attributed to the exertion of volitional effort (Lynn et al., 1990).

Alterations in the SoA are not irrelevant to objective overt responses, as positive responses to hypnotic and posthypnotic suggestions are correlated with the experience of involuntariness (Bowers, Laurence, & Hart, 1988). Furthermore, the subjective sense of conviction is an important variable for separating hypnotic suggestions from normal suggestions (Spanos & Barber, 1968). Therefore, any successful theory must be capable to explain subjective alterations in the SoA besides overt responses to hypnotic and posthypnotic suggestions.

1.4. Hypnotizability

Participants are different in their responsiveness to hypnotic and posthypnotic suggestions, that is, some are more hypnotizable than others (Bongartz, 1985; McConkey, Sheehan, & Law, 1980; Shor & Orne, 1963; Woody, Barnier, & McConkey, 2005). Hypnotizability can be defined as what is measured by standardized scales of hypnotic susceptibility (for review please see Woody & Barnier, 2008). Most of these scales consist of a normal hypnosis procedure, that is, induction, commonly by relaxation-inducing suggestions, followed by several suggestions, differing in difficulty; the (subjective or objective) compliance with these suggestions is then used to measure the responsiveness of a given participant (Woody & Barnier, 2008).

But can hypnotizability be defined independently of these standardized scales? To this end, Kirsch (1997) distinguished between (I) suggestibility as the capability to respond to suggestions outside of hypnosis, (II) hypnotic suggestibility, as the capability to respond to suggestions under the influence of hypnosis, and (III) hypnotizability as the increase in suggestibility due to the induction of hypnosis (that is, the difference between hypnotic suggestibility and suggestibility). Noteworthy, according to Kirsch (1997), common hypnotic susceptibility scales measure hypnotic suggestibility rather than hypnotizability per se. Furthermore, there are strong correlations between general suggestibility and hypnotic suggestibility ($r = .67$ for behavioral scores; $r = .82$ for subjective scores; Braffman & Kirsch, 1999), and therefore, measuring hypnotizability as defined by Kirsch (1997) is challenging.

Several studies (e.g., McConkey et al., 1980; Woody et al., 2005) have shown that hypnotic suggestibility as measured by common scales does not consist of a unitary capability, but instead is composed of several factors. In other words, the intraindividual heterogeneity in responding to different hypnotic and posthypnotic suggestions cannot be attributed simply to the difficulty of items; to the contrary, it seems that different items tap into distinguishable capabilities, and therefore, hypnotic suggestibility is composed of several different capabilities (McConkey et al., 1980; Woody et al., 2005). But as yet, the precise number and nature of these factors have proven to be elusive (for review please see Lynn et al., 2019).

Both psychosocial and cognitive factors affect how participants respond to hypnotic and posthypnotic suggestions. For instance, it is been shown that willingness and openness of participants (Green & Lynn, 2011; Lynn, Laurence, et al., 2015), their prior expectations about hypnosis (Kirsch & Lynn, 1997), rapport with the hypnotist (Lynn et al., 2019), and motivation to respond to suggestions (Jones & Spanos, 1982), are critical for hypnotic susceptibility. However, the relationship between cognitive capabilities and hypnotic suggestibility is more complex. For instance, even though several recent neurocognitive studies showed that hypnotic suggestibility is positively correlated with performance in cognitive tasks (Kirenskaya, Storozheva, Solntseva, Novototsky-Vlasov, & Gordeev, 2019; Srzich et al., 2019), other studies found no meaningful correlation between cognitive control and hypnotic suggestibility (Dienes et al., 2009; Khodaverdi-Khani & Laurence, 2016). An explanation for understanding these conflicting results can be found in the study of Terhune, Cardena, and Lindgren (2011). They suggested that dissociative tendencies might be a mediating factor between cognitive capabilities and hypnotic suggestibility. Dissociation can be defined as the disruption of the integration of thoughts, feelings, and experiences in one stream of consciousness; even though in severe forms it can be related to psychological disorders, in milder forms (i.e., dissociative tendencies), everyone may experience it (DePrince & Freyd, 1999; Kihlstrom, Glisky, & Angiulo, 1994).

As different theories usually emphasize different factors as essential variables in determining hypnotic suggestibility, we will postpone more detailed discussions about these capabilities to section ***2. Critical Review of Prominent Theories*** and ***3. Simulation-Adaptation Theory of Hypnosis***.

2. Critical Review of Prominent Theories

In this section, we will review and critically evaluate existing theories of hypnosis. Before doing so, it is useful to explicate our criteria. Simply put, any acceptable theory should parsimoniously account for a range of observable phenomena without contradiction and allow to make testable, that is, refutable predictions. When comparing such theories, those are to be preferred that (I) can account for more phenomena without contradiction (adequacy) (II) ceteris paribus, makes fewer assumptions (parsimony), and (III) ceteris paribus, generates more refutable predictions (fertility). These criteria loosely follow those outlined by philosophers of science like Karl Popper (1971). Noticeably, the hypnosis domain is so vast (Kihlstrom, 2008; Kihlstrom, 2014;

Lynn et al., 2019) that the adequacy of a corresponding theory is more important than its parsimony (Jensen et al., 2015).

We will first describe each theory and then evaluate it according to the above-mentioned criteria. Specifically, in our critical assessment, we will ask, which of the following phenomena a given theory aims to explain: (1) hypnotizability, (2) objective effects of hypnosis and posthypnotic suggestions on perceptions, (3) cognition, and (4) behavior, and (5) their effects on the subjective SoA. A special issue is (6) whether the neural underpinnings of phenomena in question taken into account by a given theory. In each case, we will consider the outcomes of empirical tests of predictions derived from a given theory.

It is important to notice that traditionally, there have been two perspectives on hypnosis, namely, the state and sociocognitive approaches. In the state approach, hypnosis has been conceived as an “altered” state of consciousness, which more recently is specified as a state of consciousness characterized by increased concentration, dissociation from the surroundings, and increased suggestibility (Elkins, Barabasz, Council, & Spiegel, 2015). Based on this definition, the state of consciousness during hypnosis differs from the waking state similar to meditation and mindfulness (Elkins et al., 2015). On the other hand, the sociocognitive approach emphasizes the social and cognitive elements of the procedure (Green & Lynn, 2011; Jensen et al., 2017; Kihlstrom, 1985; Lynn & Green, 2011; Lynn, Green, et al., 2015; Lynn et al., 2019). For instance, Kihlstrom (1985, p. 385), defined hypnosis as the process “in which one person, designated the subject, responds to suggestions offered by another person, designated the hypnotist, for experiences involving alterations in perception, memory, and voluntary action”. Hence, the hypnotic situation is of great importance as it demands conformity to social expectations (Lynn, Green, et al., 2015). However, as Jensen et al. (2015) mentioned, describing existing theories as dichotomous gives a false account of the literature. More accurately, there is a spectrum of theories, many of which only partially overlap with the traditional accounts. Next, we will discuss prominent theories of hypnosis and their strengths and limitations in interpreting empirical findings.

2.1. Response-Set Theory and Integrative Model

The response-set theory (Kirsch & Lynn, 1997; Lynn, Laurence, et al., 2015) assumes that all actions, whether in response to hypnotic or non-hypnotic suggestions, whether learned or novel, have automatic precursors and are activated by environmental cues. Hence, responses to hypnotic suggestions are also instigated automatically. In other words, hypnotic suggestions trigger the precursors of actions outlined by suggestions, which in due course bring about objective overt responses. Importantly, thoughts, feelings, and actions under the influence of hypnosis are identical with everyday quotidian activities, which means they are goal-directed, aligned with the motivations and believes of participants, and under their complete control (Lynn, Laurence, et al., 2015). With regard to changes in the subjective SoA during hypnosis, Kirsch and Lynn (1997) discuss that attributes, such as involuntariness, are “post-facto” interpretations. These interpretations are derived from both expectations about the hypnotic situation, as well as perceiving automatic precursors of actions, which are usually ignored during normal quotidian life.

To justify their claim that all actions are instigated automatically, Kirsch and Lynn (1997) refer to the contention scheduling theory of Norman and Shallice (1986) and the unconscious will theory of Custers and Aarts (2010). In essence, Norman and Shallice (1986) postulate that there is an intermediate domain of action, called contention scheduling, situated between reflexive schemata, which cannot be controlled at all, and scripts that are flexibly controlled by the supervisory attentional system (SAS; Cooper & Shallice, 2000). Norman and Shallice (1986) assume that contention scheduling is in control when several “source schemata” compete with each other in “the determination of their activation value”; here, contention scheduling ensures that the schema is selected that first exceeds a threshold. In non-demanding conditions, contention scheduling can operate without any input from the SAS. Source schemata, however, are well-learned responses and are not related to new responses; hence, when new responses are called for, the SAS is needed. Also, if a well-learned response has to be suppressed in favor of a new response, that is, in demanding conditions where contention scheduling in itself cannot provide correct and appropriate responses, the SAS has to interfere, and ensure that the correct response is selected by contention scheduling through implementing cognitive control and biasing the activation of different schemata.

The second concept on which the response-set theory is founded was introduced by Custers and Aarts (2010) and can be referred to as “the unconscious will”. Custers and Aarts (2010) argue that all basic processes essential for intention implementation, that is, recruiting the resources required for action and evaluating the reward value of the action outcomes can transpire outside of conscious awareness. In other words, an unconsciously activated goal may cause people to invest effort and select actions from their repertoire, in order to attain the goal in novel settings without being aware of the goal or its operation (Custers & Aarts, 2010).

How does the response-set theory justify its fundamental claim that “all actions, hypnotic or otherwise, are at the moment of activation triggered automatically” (Lynn & Green, 2011; p. 281)? Kirsch and Lynn (1997) gave examples that even creative actions, such as professional piano playing or communicating about new topics in one’s mother tongue, are instigated automatically and executed with little to no burden on attentional resources. However, Kirsch and Lynn (1997) did not consider that a person playing piano for the first time, or learning a foreign language, which contains new vowels and consonants unfamiliar for the speaker, needs to first acquire and learn these new trigger-response contingencies. These new responses cannot have substantial automatic precursors and learning new responses is resource-consuming. Lynn and Green (2011) justified their claim by referring to the concept of the unconscious will (Custers & Aarts, 2010). However, in reviewing priming effects, Custers and Aarts (2010) mention that the *intention* to perform an action can spring from outside of consciousness, and also that consciousness is not necessary to *evaluate the reward value* of an action. In other words, the intention to execute an action, already existing *in one's repertoire*, can be implemented without conscious awareness; however, this does not mean that all actions are triggered automatically at the moment of activation. New actions without established trigger-action contingencies, are not part of one's repertoire and need to be learned first. Can hypnotic suggestions affect new responses, which do not have any automatic precursors?

As reviewed in section ***1.2. Objective Changes in Overt Behavior, Perception, and Cognition***, executive functions (EF; Baddeley, 2003; Diamond, 2013; Miyake et al., 2000), which are closely related to the concept of the SAS, can be affected by task-relevant hypnotic and posthypnotic suggestions. Consequently, suggestions are able to both, trigger automatic precursors of actions, as well as to establish new trigger-response contingencies. Therefore, even though capable of accounting for a range of responses to hypnotic and posthypnotic suggestions, for instance, triggering *well-learned or well-known actions*, the response-set theory has shortcomings in explaining the effects of suggestions when it comes to situations where novel responses are required. For instance, situations that require substituting automatic, prepotent but task-irrelevant responses with new ones, or learning new trigger-action contingencies when receiving appropriately-tailored suggestions.

In a recent version of their theory called the integrative model, Lynn, Laurence, et al. (2015) and Lynn et al. (2019) focused on changes in the subjective SoA during hypnotic-suggestion-triggered responses. Importantly, Lynn, Laurence, et al. (2015) distinguished between suggestibility and hypnotizability, based on the suggestion of Kirsch (1997) (discussed in section ***1.4. Hypnotizability***). As in their previous accounts, the authors maintained that since there is a high correlation between suggestibility and hypnotic suggestibility (Braffman & Kirsch, 1999), objective responses to hypnotic suggestions are caused by the same mechanisms underlying responses to normal suggestions. However, in the new version of their theory, they discussed that there is only one difference between normal suggestions and hypnotic suggestions, that is, hypnosis induces the feeling of involuntariness in hypnotized participants when they are executing hypnotic suggestions. To understand this kind of passivity, Lynn, Laurence, et al. (2015) referred again to the Custers and Aarts' (2010) theory of the unconscious will. Except that here, they suggest that the response that is triggered automatically is the unconscious will to follow experimenters' expectations.

One should keep in mind that most of the studies on which Custers and Aarts (2010) grounded their theory are related to priming (e.g., Lau & Passingham, 2007; Naccache & Dehaene, 2001; Strahan, Spencer, & Zanna, 2002). For instance, Lau and Passingham (2007) used a task, in which each trial could be related to one of two sub-tasks measuring two different cognitive control processes. Before each trial participants were primed, correctly or incorrectly, about the subtask involved in the trial. This manipulation significantly affected performance, and fMRI recordings during task completion revealed that priming had activated the brain areas related to the primed task, demonstrating that diminished performance in incorrectly primed trials is not related to distraction from the correct subtask but due to preparation for the incorrect subtask. Finally, when asked after the study, participants denied noticing the experimental manipulation and believed that it had not affected their performance. Quintessentially, priming stimuli are very short, which can affect behavior outside of conscious awareness. In contrast, hypnotic suggestions are clear and explicit and, therefore, hypnotized participants are unlikely to be unaware of the manipulation.

If their unconscious will to follow experimenters' intention were the only determinant of changes in the SoA of hypnotized participants, the nature of the suggestions should be unrelated to the experience of involuntariness felt when receiving different suggestions, as participants should have clear expectations about the experimenters' intentions, independent of the wordings of suggestions. However, this contrasts with the hypnosis literature emphasizing the importance of the type of suggestions for the experience of involuntariness. This is reflected in contrasting effects of, for instance, goal-directed imaginative versus non-imaginative suggestions (Spanos, 1971), direct versus indirect suggestions (Lynn, Neufeld, & Matyi, 1987), and elaborated-indirect versus short-direct suggestions (Matthews, Bennett, Bean, & Gallagher, 1985), where the former variants supposedly cause a higher sense of involuntariness or passivity as compared to the latter. Here one should point out that long-indirect suggestions in comparison to short-direct suggestions may signal participants to feel less involuntary; however, the exact opposite effect has been reported (Matthews et al., 1985). In other words, suggestions are not necessarily inducing specific expectations in participants in terms of a greater or smaller change in their SoA but there may be a mechanism that makes participants feel more involuntary in response to some suggestions than to others. Even Lynn, Laurence, et al. (2015) themselves emphasized that the wording of suggestions is a determining factor for the degree of change in the SoA. Hence, besides performance enhancements in executive function tasks, also in regard to the SoA, the response-set theory's account appears oversimplified.

2.2. Dissociation and Decoupling Theories

There are several accounts of the dissociation theory, which despite their great differences, share the basic concept that hypnosis is a state of mind during which normal conscious cognitive control processes are inaccessible or disrupted, and hence, their functions are delegated to the subconscious or lower-level processes. Amongst dissociation theories, several prominent variants can be distinguished.

2.2.1. Neo-Dissociation Theory

The “neo-dissociation” account (Hilgard, 1973, 1977) assumes that hypnosis builds a communication barrier, or “amnestic barrier” (Woody & Bowers, 1994), between the normal stream of consciousness and the subconscious “hidden observer”. Even though participants maintain their normal cognitive functioning, a part of perceptual information and/or cognitive control processes become inaccessible to consciousness, which explains the changes in the subjective SoA. Hence, the sense of passivity accompanying hypnotic-suggestion-induced responses is due to the inaccessibility of some cognitive processes and information, as they are hidden behind an amnestic barrier. The neo-dissociation account is currently out of favor even among advocates of dissociation theory (Jamieson & Woody, 2007; Woody & Bowers, 1994), mainly because amnesia during hypnosis is a rare and controversial experience, and grounding a definition on an exceptional phenomenon is perilous (Kirsch & Lynn, 1998; Woody & Bowers, 1994).

However, some parts of the neo-dissociation theory have been integrated into other theories. For instance, Lynn and Green (2011), proposed a path for rapprochement by suggesting that the response-set theory is closely related to the neo-dissociation theory because both theories assume that hypnotized participants retain their normal cognitive functions. However, similarities between the two theories end here, as for explaining hypnotic phenomena the neo-dissociation theory assumes an amnestic barrier whereas the response-set theory maintains that all actions are automatic. The neo-dissociation theory's claim that an amnestic barrier divides consciousness into two streams limits its applicability to the few participants experiencing hypnotic amnesia (Hilgard, 1973, 1977). Further, the response-set theory's assumption that all actions are initiated automatically precludes its applicability to conditions without preexisting automatic response-action contingency.

2.2.2. Dissociation Theory

The second variant of the dissociation theory was first proposed by Woody and Bowers (1994) and later was reframed as the decoupling theory (Egner et al., 2005; Egner & Raz, 2007; Jamieson & Sheehan, 2004) and the dissociated control theory (Jamieson & Woody, 2007). Here, the basic assumption is that during hypnosis frontal lobe functions are disabled or disrupted and, therefore, the sense of passivity is not an illusion, in contrast to what is maintained by the neo-dissociation account (Woody & Bowers, 1994). Instead, the sense of passivity occurs since higher cognitive control processes are disrupted and participants, rightfully, cannot relate their actions to intention implementation or planning (Brown & Oakley, 2004; Jamieson & Woody, 2007; Woody & Bowers, 1994). Variants of dissociation theories mainly diverge in answering which higher-order cognitive functions are supposedly disrupted during hypnosis. Employing contention scheduling (see section ***2.1. Response-Set Theory and Integrative Model***), Woody and Bowers (1994) claimed that hypnosis disables the SAS and therefore, participants will act only based on lower-level cognitive control processes, that is, contention scheduling. However, according to Norman and Shallice (1986), contention scheduling is a system of functioning where no novel action is required. In other words, contention scheduling is related to situations, in which several source schemata are activated, and contention scheduling is only responsible to select the first schema that reaches a certain threshold. If cognitive control is required, for example, if a prepotent but irrelevant response has to be inhibited, the SAS must interfere. Consequentially, as Brown and Oakley (2004) and Jamieson and Woody (2007) noticed, if the suggestion of Woody and Bowers (1994) that the SAS is disabled during hypnosis was correct, participants should have been unable to perform any executive function tasks during hypnosis because such tasks require the SAS. Although there is a dispute whether participants perform executive function tasks better or worse under the effects of neutral hypnosis (i.e., hypnosis without task-relevant suggestions) (Egner et al., 2005; Nemeth et al., 2013; Zahedi et al., 2017), it is undisputed that performance under the influence of hypnosis is similar to normal conditions (Jamieson & Woody, 2007; Parris, 2017). Therefore, hypnotized participants can still deploy executive functions, which shows that during hypnosis the SAS cannot be (completely) disabled.

2.2.3. Decoupling Theory

In order to account for the essentially unimpaired executive functions under the influence of hypnosis Jamieson and Sheehan (2004) and Egner et al. (2005) suggested that only part of the SAS is disabled (decoupled) under hypnosis, namely, cognitive monitoring. The decoupling account is based on the conflict monitoring theory proposed by Botvinick, Braver, Barch, Carter, and Cohen (2001), which distinguishes cognitive control from monitoring processes at both anatomical and functional levels (Botvinick, Cohen, & Carter, 2004). Monitoring for cognitive conflicts takes place in the anterior cingulate cortex (ACC) whereas cognitive control processes are initiated in the dorsolateral prefrontal cortex (DLPFC). Indeed, many studies (e.g., Botvinick et al., 2004; Carter et al., 2000; Kerns et al., 2004) indicate that ACC activation is related to evaluative but not regulative processes, in other words, ACC activation is related to the detection of conflict, and signals the necessity for cognitive control implementation. However, the ACC is not directly engaged in implementing cognitive control. Referring to the conflict monitoring theory, the decoupling account claims that hypnotized participants can still perform executive function tasks under the influence of hypnosis since they still can initialize their executive functions. For instance, if necessary, hypnotized participants can inhibit a prepotent response and, instead, select a more relevant one for the task at hand, comparable to normal conditions, even though probably less successfully. However, this implementation of executive functions is supposed to be inflexible and cannot be modulated by internal monitoring signals, since monitoring and cognitive processes are disconnected (Egner et al., 2005; Jamieson & Sheehan, 2004).

Two points need to be discussed about the newt dissociative conjunction. First, the results of Kerns et al. (2004) mentioned above had shown that lower activation of the ACC in a given trial predicts decreased performance (i.e., longer reaction times) in the next trial. Following the suggestion of Egner et al. (2005) that during hypnosis the ACC and DLPFC are disconnected, one should expect that hypnotized participants do not detect the need for implementing cognitive control, which in turn should severely deteriorate performance (e.g. increase reaction times). However, many studies failed to observe performance decrements as a result of hypnosis (e.g., Egner et al., 2005; Zahedi et al., 2017). To address this contradiction, Jamieson and Woody (2007) proposed that hypnosis affects the outgoing signals from the rostral section of the ACC and not the dorsal part. They explained further that the dorsal ACC, which is related to conflict monitoring, should be unaffected by hypnosis but the rostral ACC, which is associated with error monitoring and feedback evaluation, is hampered by hypnosis. Therefore, they claimed, even though hypnotized participants can perform well in executive function tasks, they cannot enhance their performance under the effects of hypnosis. However, it must be considered that the different roles assigned to the rostral ACC originate from competing theories about the ACC function. The conflict monitoring account considers the ACC as being responsible for conflict detection (Botvinick, 2007; Botvinick et al., 2001; Botvinick et al., 2004). In contrast, in the outcome evaluation and decision making account, the ACC monitors action outcomes and guides decision making based on its evaluation (Botvinick, 2007). That means, these two sets of functions are assigned to the whole ACC, rather than a special part of it. For instance, many studies have shown that both prediction-based signals and outcome evaluation signals originate from the posterior and middorsal regions of the ACC (Botvinick, 2007; Jahn, Nee, Alexander, & Brown, 2014). Therefore, the proposition of Jamieson and Woody (2007) that there are two sets of overlapping functions related to the ACC, which can be anatomically distinguished does not align with empirical findings. Therefore, the claim of Jamieson and Woody (2007) that during hypnosis one set of ACC actions is intact whereas the other set is blocked appears unwarranted.

Second, and more importantly, as mentioned above, one of the major predictions of the dissociation theory is the alleged incapability of hypnotized participants to enhance their performance in executive function tasks. However, as discussed in section ***1.2. Objective Changes in Overt Behavior, Perception, and Cognition***, the capability of task-relevant posthypnotic suggestions to enhance performance in executive function tasks is one of the best-established findings in the hypnosis literature (e.g., Iani et al., 2009; Iani et al., 2006; Lindelov et al., 2017; Raz et al., 2005; Raz et al., 2006; Zahedi et al., 2019; Zahedi, Luczak, et al., 2020; Zahedi et al., 2017). Egner and Raz (2007) tried to reconcile the performance enhancements in executive function tasks under the influence of task-relevant posthypnotic suggestions with the decoupling account. However, in doing so they retreated to the basic form of contention scheduling. They suggested that hypnotized participants who receive task-relevant posthypnotic suggestions, despite being hampered in using their SAS, can perform more automatically akin to following contention scheduling. As mentioned above, contention scheduling is only applicable to source schemata, that is, well-learned, automatic responses. As discussed by Zahedi, Sturmer, et al. (2020), the suggestion of Egner and Raz (2007) is only plausible if: (1) Participants have learned a task-appropriate, novel response to the point where it has become semi-automatic and, therefore, this “new” response is capable of overriding a prepotent response without employing the SAS. (2) Bottom-up processes have been modified to disrupt the prepotent response (e.g., becoming temporarily dyslexic during the Stroop task) and therefore, the SAS is not be required anymore. The former assumption contradicts the basic assumptions of the dissociation theory, as learning requires the coordination between cognitive control and monitoring (e.g., Gobel, Parrish, & Reber, 2011; van der Graaf, Maguire, Leenders, & de Jong, 2006). The latter option is at variance with observations that posthypnotic suggestions can affect performance in updating tasks (e.g., Lindelov et al., 2017; Zahedi, Sturmer, et al., 2020), where changes in bottom-up processes cannot significantly enhance performance (cf. Zahedi, Sturmer, et al., 2020). Hence, the decoupling account appears to be unsuited to explain performance enhancements due to hypnotic and posthypnotic suggestions.

2.3. Unified Cognitive Model

In their unified cognitive model, Brown and Oakley (2004) also tried to reconcile the response-set and dissociation theories. Brown and Oakley (2004) outlined different levels of cognitive control based on the contention scheduling theory described above (see ***2.1. Response-Set Theory and Integrative Model***). Then they distinguished between hypnotizability and suggestibility, based on the proposition of Kirsch (1997) (see ***1.4. Hypnotizability***) and defined two styles of responding to hypnotic suggestions. When hypnotized participants respond to suggestions by directly activating the appropriate schemata through contention scheduling, without incorporating the SAS, it is labeled concentrative style. In contrast, when hypnotized participants deliberately use their SAS in order to guide and help contention scheduling to choose the proper source schema, it is called constructive style. Noticeably, these postulated styles resemble the dissociation and response-set theories, respectively. Brown and Oakley (2004) argued that suggestibility outside of hypnosis is related to the constructive style but hypnotizability (i.e., increased in suggestibility due to hypnotic induction) is more closely aligned with the concentrative style. However, participants can use both styles interchangeably, depending on their inner motivations and environmental signals.

An ambiguous point in the unified cognitive theory is whether these styles allude to states (i.e., temporary modes of operation), or traits (i.e., stable characteristics). One should consider that the concentrative and constructive styles in Brown and Oakley's (2004) account are incompatible. That is, in concentrative style the SAS is inhibited but in the constructive style the SAS is heavily utilized. Therefore, the unified cognitive theory allows four possible specifications. (1) The styles are *suggestion-related states*: hypnotized participants can use the concentrative or constructive styles in responding to different suggestions; which one they chose, may depend on the wordings of suggestions and external cues. This leads to the prediction that there are two separable categories of suggestions. Empirically, there are three to four distinguishable categories of suggestions, namely, ideomotor, challenge, and cognitive suggestions (McConkey et al., 1980; Woody et al., 2005). However, suggestions from all these categories involve imagination (related to the constructive style), which is probably the shared characteristic of all suggestions (for review please see Landry, Lifshitz, & Raz, 2017).

(2) Styles are *induction-related states*: even though styles of responding are states, they are fixed for a given participant during a given hypnotic procedure but may change in a different procedure. Which style is used, depends on the rapport between the participant and hypnotist, or other external cues. Following this interpretation, one expects that hypnotic suggestibility scales have low reliability. However, HGSHS-A scores are very reliable with, $stability\ coefficient\ 0.82\ (15 - year\ retest)\ and\ .71\ (25 - year\ retest)$ (Piccione, Hilgard, & Zimbardo, 1989).

(3) Styles are related to *general traits*: there are two distinguishable groups of individuals, one relying on the constructive style, and the other, on the concentrative style for responding to suggestions. These differences may originate from differences in the cognitive capabilities of participants. In this form, the unified cognitive theory can explain the results of Terhune et al. (2011), who had observed there are two groups of high-hypnotizables, one with higher dissociative tendencies and the other with higher imaginative capabilities. Nevertheless, the unified cognitive theory still inherits all the issues discussed with regard to the response-set and dissociation theories (see ***2.1. Response-Set Theory and Integrative Model*** and ***2.2. Dissociation and Decoupling Theories***). For instance, as in the concentrative style, the SAS is supposed to be disabled, one expects that some hypnotized participants cannot perform executive function tasks at all, which contrasts with published reports (cf. Jamieson & Woody, 2007; Parris, 2017). Further, considering the concentrative style, the unified cognitive theory can only explain enhancements in performing executive function tasks under the influence of suggestions by attributing them to bottom-up processes, which again is at variance with empirical findings (cf. Zahedi, Sturmer, et al., 2020).

(4) Finally, the constructive style is related to responding to suggestions in general, and the concentrative style is employed for responding to suggestions under the influence of hypnosis.

This assumption is contradicted by existing observations. If participants exclusively used the concentrative style during hypnosis, they should be very responsive to suggestions only during hypnosis, but not so much when receiving suggestions outside of hypnosis. However, it has been shown that hypnotic suggestibility and general suggestibility are highly correlated (e.g., Braffman & Kirsch, 1999; Kirsch, 1997).

Summarizing, the unified cognitive model does not go beyond the response-set and dissociation theories and therefore, the problems discussed in sections ***2.1. Response-Set Theory and Integrative Model*** and ***2.2. Dissociation and Decoupling Theories*** also pertain to the unified cognitive theory.

2.4. Predictive Coding Models

The predictive coding approach has gained prominence in several fields and has recently been applied to hypnosis, as well. In essence, the predictive brain model (Fig. 1A, B), also called the Bayesian brain or predictive coding model (for review please see Yon, de Lange, & Press, 2019), postulates that the brain acts like a scientist trying to understand the world via Bayesian-type modeling. Bayesian systems involve three integral elements, priors (i.e., epistemological uncertainty), evidence, and posteriors (i.e., updated epistemological uncertainty). In the predictive coding model, priors are top-down predictions (i.e., efferent signals), which are based on our cognitive or heuristic model of the world, and constantly interact with exteroceptive, perceptual, and somatosensory proprioceptive evidence (i.e., afferent signals). Through these interactions, posteriors are formed, that is, priors are updated by considering the probability of the priors given the evidence (Clark, 2013).

The free-energy principle holds that "any living or non-living self-organizing system that resides at equilibrium with its environment must minimize its free energy" (Friston, 2010, p. 127).

Combining the free energy principle and the predictive coding model, it is conspicuous that if a prediction error (i.e., being in a surprised state) arises, that is, if there is a disparity between predictions (i.e., prior distributions) and sensory feedback (i.e., evidence), the system tries to return to a stable condition without error signals. This can be achieved by active inference or perceptual inference. Perceptual inference (Clark, 2013) refers to situations, where prediction errors are eradicated by updating priors. That is, by changing the cognitive model based on which predictions are formed, predictions become aligned with sensory feedback (Fig. 1A). Hence, perceptual inference results in perceptions. Active inference, on the other hand, refers to conditions, where prediction errors are eliminated by modifying actions in order to align outcomes with predictions (Clark, 2013; Friston, 2010; Yon et al., 2019). Therefore, active inference results in actions. During active inference (Fig. 1B), top-down predictions (descending proprioceptive predictions) are formed and sent through cortico-cortical and corticospinal projections to target muscles. However, prediction errors (i.e., afferent signals) are used in reflex arcs to correct the action and match it with predictions. Hence, prediction errors are gradually downregulated in a process called sensory attenuation, and their projection beyond thalamic gates is inhibited, therefore, they are not integrated into the system beyond reflex arcs (Brown, Adams, Parees, Edwards, & Friston, 2013; Yon et al., 2019). For instance, when an agent wants to grasp a glass of water, first, a prediction is made about the next location of the hand. Since at the beginning the hand is still in its original location there will be a disparity between the prediction and sensory feedback. Based on the free energy principle, the agent tries to reduce the error signal. Here, the disparity is eliminated by active inference. That is, sensory feedback is used in reflex arcs to correct the position of the hand. Therefore, when sensory feedback reaches thalamic gates, it is downregulated through sensory attenuation. As the agent's hand starts to move based on the prediction, the disparity between the prediction and sensory feedback is resolved.

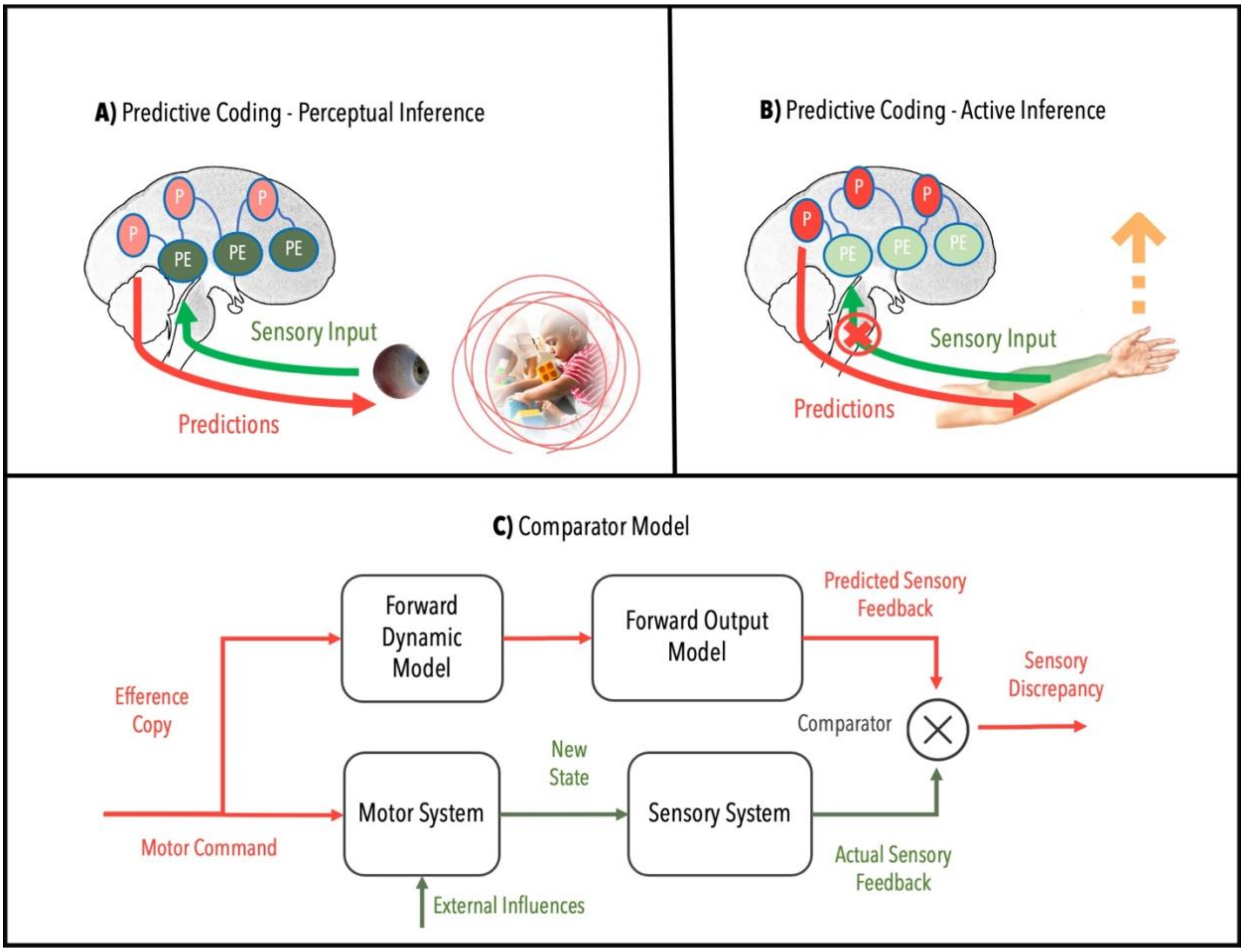


Figure 1. The schematic representation of (A) Perceptual inference as suggested by the predictive coding model; (B) Active inference as suggested by the predictive coding model. "P" refers to predictions and "PE" to prediction errors; as evident, there are multiple layers where prediction and prediction errors interact with each other. (C) The comparator model.

One of the important concepts in the predictive coding model is that efferent signals, which are sent through descending cortico-cortical and corticospinal projections, are predictions and not motor commands (Adams, Shipp, & Friston, 2013). This is in contrast with the comparator model (Blakemore et al., 2003; Frith, Blakemore, & Wolpert, 2000), which later has been transformed into the predictive coding model. In the comparator model (Fig. 1C), motor commands are sent to muscles, and simultaneously an efference copy of these commands is used to shape a forward dynamic and a forward output model. For instance, when a person is engaged in a physical action (moving the hand in order to grasp a glass of water), an efferent copy of the motor command is used to build a forward dynamic model, that is, a prediction of what will be the next state of the system to be compared to the desired state (if I move my hand in direction X and with velocity Y, I should reach and grab the glass at time Z). Then, based on the causal representation of the motor system, the system forms a forward output model, which predicts the sensory input to be received if the motor system acts in that particular way (Miall & Wolpert, 1996). The production of the forward dynamic and output models are based on the operator's knowledge about the system's behavior and are compared continuously with proprioceptive signals. Now, if there are any disparities between the forward output model and the actual sensory feedback (my hand is in position Z instead of X), the behavior will be modified to diminish the discrepancy (the hand will be moved in the other direction to compensate the disparity). However, in the predictive coding model, in contrast to the comparator model, there are no motor commands, and the only descending signals are predictions. Hence, the necessity for postulating the existence of an efference copy of motor command for producing forward models (both dynamic and output models) is eliminated. The predictive coding model has been employed in two very different theories of hypnosis for explaining changes in the subjective SoA in hypnotized participants.

2.4.1. Interoceptive Predictive Coding

The first application of predictive coding to hypnotic phenomena (i.e., interoceptive predicting coding) was made by Jamieson (2016). Interoceptive predictive coding extending the decoupling account, based on results of Blakemore et al. (2003). Blakemore et al. (2003) had used hypnosis to scrutinize neural underpinnings of misattribution of movements to alien sources in different psychological mental disorders, such as delusion of control in schizophrenia. Their experiment had three conditions, where hypnotized healthy participants would either move their hand upward or notice it is being moved upward. (1) They should have moved their hand actively by themselves. (2) They should have noticed that their hand would be moved by a mechanical device attached to them. And (3) participants were informed that their hand would be moved by the device, however, in reality, the device was inactive. The third condition resembles the common hand levitation suggestion. After receiving these suggestions, the participants' hands started to move upward in all conditions. From the results of the third condition, Blakemore et al. (2003) concluded that under the influence of the hand-levitation suggestion (1) participants must have formed appropriate motor commands and a functioning forward dynamic model. (2) With positron emission tomography (PET) Blakemore et al. (2003) observed that hand levitation performance in condition 3 was correlated with increased glucose metabolism in the parietal cortex and cerebellum. They suggested that the increased activity indicates deactivation of the forward output model, causing a persistent, unresolved error signal, which causes participants to misattribute their own action to an external source.

Jamieson (2016) reframed the results of Blakemore et al. (2003) into a predictive coding model. He argued that since other studies had shown that under the influence of hypnotic suggestions, both blocking a movement (i.e., hypnotic paralysis) or inducing a movement (e.g.., hand-levitation), disrupt the connection between the frontal cortex and the parietal-cerebellum network (e.g., Cojan et al., 2009; Deeley et al., 2013; Walsh, Oakley, Halligan, Mehta, & Deeley, 2015). Therefore, hypnotic-suggestion-induced actions are governed by different processes in comparison to normal actions. Further, Jamieson (2016) argued that the results of Blakemore et al. (2003) suggest that hypnotized participants cannot perceive the source of their actions because their forward output model is disrupted “at the point of source or at the points of transmission and terminus" (Jamieson, 2016; p. 320); as the neural motor network consists of highly divergent pathways, the possible point of disruption must be at the source. In conclusion, Jamieson (2016) suggested that misattribution of movements to external sources in hypnotized participants must be related to the formation of internal models based on hypnotist's suggestions. Further, these internal models are not implemented through normal pathways but by lower-level perceptual and proprioceptive units. Therefore, no predictions will be formed and due to their absence, participants cannot recognize the source of their actions.

In evaluating Jamieson's (2016) predictive coding model, it seems that he utilized a mixture of both the comparator and predictive coding models. In the predictive coding model, suggested by Friston (2010), only predictions and not motor commands are formed and sent through downward projections (Adams et al., 2013). Therefore, no efference copy of motor commands or forward models will be generated. Following Jamieson's (2016) proposition that no prediction is generated during hypnosis, if actions are explained by the predictive coding model, one should expect no action, at all. Jamieson (2016) further claims that frontal lobe functioning is diminished during hypnosis. However, multiple studies have shown increased rather than decreased frontal lobe activity during hypnotic-suggestion-induced actions and enhanced functional connectivity between the frontal lobe and some sections of the parietal lobe (e.g., Cojan, Archimi, Cheseaux, Waber, & Vuilleumier, 2013; Cojan et al., 2009; Ludwig et al., 2015; Pyka et al., 2011). Therefore, the interoceptive predicting coding model has severe internal inconsistencies, which makes the theory infertile.

2.4.2. New Predictive Coding Model

The second application of predictive coding to hypnotic phenomena was put forward by Martin and Pacherie (2019) as an expansion of sensory attenuation in active inference (Brown et al., 2013). Focusing on motor suggestions, Martin and Pacherie (2019) proposed that, in contrast to active inference under normal conditions, during hypnotic-suggestion-induced actions somatosensory and proprioceptive signals are not downregulated. Instead, they are incorporated into the system even beyond reflex arches and thalamic gates. Further, somatosensory feedback is even more precise in comparison to normal conditions. That is, sensory feedback is given a higher weight in the (Bayesian) model. However, if predictions do not have a higher weight in comparison to prediction errors, there will be no action. Hence, the predictions will also be more precise in comparison to normal conditions. Noticeably, this scenario is neither related to the normal perceptual inference nor active inference. In normal conditions, during active inference somatosensory feedback is downregulated and given lower weight than predictions. In contrast, during perceptual inference, somatosensory feedback is given higher weight than predictions, which causes perceiving a stimulus and does not lead to a movement. Martin and Pacherie (2019) continue that during hypnosis, predictions are based on hypnotic suggestions and therefore they are more precise in comparison to normal conditions. In a periodical manner, these precise predictions will be given higher weight in comparison to prediction errors, which enables actions to be started and continued. Further, as the relative weight of predictions and prediction errors will be periodically changed, the commonly observed phenomenon that hypnotic-suggestion-induced actions are hesitant and slow can be explained. Consequently, as both predictions and somatosensory feedback are precise, a sizeable prediction error is generated, which is precise, persistent, and unresolved. In order to interpret their strong prediction error signal, hypnotized participants will attribute their actions to external forces rather than self-generated volition.

Even though the predictive coding account of Martin and Pacherie (2019) appears to be very plausible, it cannot explain at least three sets of observations. First, different participants may use different strategies to implement the same suggestion. For instance, Galea, Woody, Szechtman, and Pierrynowski (2010) investigated the physiological effects of hypnotic-paralysis by asking high-hypnotizable participants to feel rigidity and stiffness in their arms and then asked them to move their hands with the implication that it cannot be done. To implement this suggestion the participants seemed to use very divergent strategies, namely, (1) some *simultaneously activated agonist and antagonist* muscles (biceps and triceps), (2) some others *only activated the antagonist* (triceps) but inactivated the agonist, and some (3) *did not activate any muscle* group. These results show that participants individually formulate unique and different predictions based on the same suggestion. This contrasts with the claim of Martin and Pacherie (2019) that predictions are more precise during hypnosis in comparison to normal conditions because they come from the hypnotist and are reinforced by the hypnotist's words. If predictions are generated by the participants, similar to normal conditions, and not by the hypnotist, why should predictions under the influence of hypnosis be more precise than in normal conditions?

Second, there are also intraindividual differences in responding to the same suggestion depending on how they are phrased. For example, in comparison to succinct and short suggestions imaginative and elaborated ones may induce a higher sense of passivity and diminish the subjective SoA more strongly (Lynn et al., 1987; Matthews et al., 1985; Spanos, 1971). It is hard to explain the intraindividual differences in response to different wordings with the account of Martin and Pacherie (2019). That is, based on the new predictive coding model when the same person receives suggestions from the same hypnotist aiming to induce the same action, priors and the weights allocated to them should be invariant.

Third, the main focus of Martin and Pacherie (2019) was on motor suggestions and their account does not easily transfer to other phenomena. Here are some examples: (I) as noticed by the authors themselves, in hallucinatory suggestions, participants seem to have sensory input from an imaginary source, which is given higher value in comparison to sensory feedback from the outside reality. Why is the same process not governing motor suggestions? That is, during motor suggestions also feedback from imaginary stimuli might be given higher weight in comparison to feedback from the real world, and predictions could be formed based on imaginary stimuli. (II) One of the most reliable observations in the field of hypnosis is the effectiveness of pain-reducing suggestions (for review please see Thompson et al., 2019). Here, attention to noxious stimuli is reduced rather than increased, which again contrasts with the account of Martin and Pacherie (2019). (III) As discussed in section ***1.2. Objective Changes in Overt Behavior, Perception, and Cognition***, one of the most robust hypnotic phenomena is that posthypnotic suggestions can help hypnotized participants to learn new trigger-response contingencies. However, the account of Martin and Pacherie (2019) cannot explain this phenomenon. (IV) Martin and Pacherie (2019) expected that training of suggestions before hypnosis would decrease the sense of involuntariness during hypnosis. However, Gorassini and Spanos (1986) have shown that such training can enhance suggestibility.

2.5. Cold Control Theory

In their cold control theory, Dienes and Perner (2007) accounted for changes in the subjective SoA during hypnosis by focusing on ascriptive metacognition. Ascriptive metacognition emphasizes the judgment of agency, differentiating it from other forms of metacognition that focus on the judgment of performance (Dienes, Beran, Brandl, Perner, & Proust, 2012; Miele, Wager, Mitchell, & Metcalfe, 2011). Based on the higher-order thought model (Rosenthal, 2002; Rosenthal, 2006), Dienes and Perner (2007) distinguished first-order thoughts from second- and third-order thoughts. First-order thoughts refer to the awareness of sensations (e.g., I see a black cat), second-order thoughts refer to the consciousness of being aware of sensations (I know that I see a black cat), and third-order thoughts designate the consciousness of being conscious of sensations (I am aware to know that I see a black cat). Dienes and Perner (2007) contended that hypnosis does not affect first-order thoughts (perception and cognition) but may render second- and third-order thoughts dysfunctional and inaccurate. Specifically, they assumed that high-hypnotizable participants can bypass second and third-order thoughts altogether, while medium-hypnotizables are only capable of bypassing third-order thoughts. In line with findings that relate ascriptive metacognition to the DLPFC (e.g., Miele et al., 2011), the cold control theory attributes the dysfunctionality of higher-order thoughts during hypnosis to the disruption in DLPFC activity.

Several studies have tested this postulation. For instance, Dienes and Hutton (2013) showed that low-frequency repetitive transcranial magnetic stimulation (rTMS) of the frontal lobe, in comparison to rTMS of sensory and motor cortices (control condition), increased the responsiveness to some hypnotic suggestions. However, it must be considered that the hypnotic suggestions were related to motor actions. Hence, it is possible that differences between the stimulation conditions were due to decreased responsiveness in the control condition, where sensory and motor cortices were stimulated, rather than enhanced responsiveness in the frontal-stimulation condition.

Furthermore, Semmens-Wheeler, Dienes, and Duka (2013) found that alcohol consumption can increase subjective responsiveness to hypnotic suggestions. Because, in lower doses, alcohol can attenuate fear responses by affecting limbic and visual brain regions (Gilman, Ramchandani, Davis, Bjork, & Hommer, 2008) the participants of Semmens-Wheeler et al. (2013) may have been more euphoric and less stressed under alcohol and, hence, might have followed hypnotic suggestions with less restraint, boosting alterations of the SoA. The conclusiveness of the findings of Semmens-Wheeler et al. (2013) is further limited by the absence of significant alterations in objective responsiveness to hypnotic suggestions. Therefore, under the influence of alcohol, the participants might have been less able to judge their SoA rather than being truly more responsive to suggestions.

Finally, Terhune and Hedman (2017) used a task assessing the judgment of agency (Metcalfe, Van Snellenberg, DeRosse, Balsam, & Malhotra, 2012), where participants had to select target stimuli with the mouse cursor while avoiding other stimuli that moved across the monitor. By manipulating cursor lag Terhune and Hedman (2017) showed that although the judgment of performance in high-hypnotizables was equivalent to other participants, their SoA was less affected by cursor lag. A caveat here is that Terhune and Hedman (2017) used relatively short cursor lags (i.e., 50 and 100 ms) in comparison to studies investigating the SoA in schizophrenic patients with the same task (i.e., 250 ms and 500 ms; Metcalfe et al., 2012). Further, they had not applied other manipulations, such as turbulence of cursor position, as usually are used in addition to cursor lag, in order to affect the SoA more robustly.

Explaining the sensation of involuntariness during hypnosis by the proneness to disruption of the judgment of agency has several problems. Let’s consider existing evidence at the neural level. The disruption of agency in high-hypnotizable participants may be viewed as a state induced by hypnosis or as a trait. Concerning the state perspective, several studies have shown brain activity in the lateral prefrontal cortex (LPFC) and DLPFC is increased when cognitive tasks are performed under the influence of hypnosis, (Cojan et al., 2013; Cojan et al., 2009) or at least did not decrease (Egner et al., 2005). These findings indicate that these brain areas, presumably involved in ascriptive metacognition (Miele et al., 2011), are not disrupted by hypnosis.

Concerning the trait perspective, even outside of hypnosis, high-hypnotizables have shown higher LPFC activity than low-hypnotizables during flanker tasks (Cojan, Piguet, & Vuilleumier, 2015), or increased frontal activity (as indicated by a bigger frontocentral P300) during an oddball task (Kirenskaya et al., 2019). These findings argue against diminished metacognition in high- compared to low-hypnotizables. Furthermore, it has been shown that the LPFC and DLPFC are essential regions in the executive functions' network (Miyake & Friedman, 2012; Niendam et al., 2012; Rottschy et al., 2012; Wager & Smith, 2003). However, there seems to be no evidence that high- and low-hypnotizables perform differently in executive function tasks, neither outside of hypnosis (Dienes et al., 2009), nor under the influence of task-irrelevant hypnotic suggestions (Egner et al., 2005; Zahedi et al., 2017).

At the cognitive level, if one assumes that hypnosis induces a state where higher-order thoughts are disrupted, and being in this state is a prerequisite for responding to suggestions, there should be a great difference between general suggestibility and hypnotic suggestibility, as defined by Kirsch (1997). This prediction, however, is refuted by many observations (Braffman & Kirsch, 1999; Kirsch, 1997; Lush et al., 2020; Lynn et al., 2019; Palfi, Parris, McLatchie, Kekecs, & Dienes, 2020; Parris & Dienes, 2013). Alternatively, if proneness to disruption of higher-order thoughts is considered as a trait of high-hypnotizables, different wordings of suggestions should have no or little effect on the subjective SoA during hypnosis. As discussed above, there is no evidence supporting this prediction, as well (Lynn et al., 1987; Matthews et al., 1985; Spanos, 1971).

Finally, one of the most robust findings in the hypnosis literature is that task-relevant posthypnotic suggestions can enhance the performance of high-hypnotizables in various executive function tasks, as reviewed above in section ***1.2. Objective Changes in Overt Behavior, Perception,***

and Cognition. The disruption of higher-order thoughts, the state or trait perspectives alike, cannot explain these enhancements. Further, as discussed by Zahedi, Sturmer, et al. (2020) and also below (see ***3.3. Learning and Other Cognitive Changes***), a plausible mechanism underlying the effects of posthypnotic suggestions is cognitive-simulation of the task at hand. Cognitive-simulation provides a ground for the mental training of a suggested strategy, which usually is the same strategy introduced during task instructions. Mental practice may aid hypnotized participants to learn new trigger-action contingencies and to implement executive functions more efficiently and fruitfully in the targeted task(s). DLPFC and LPC are used extensively for learning new trigger-action contingencies (e.g., Gobel et al., 2011; van der Graaf et al., 2006). Hence, if the activity of these regions is disrupted in high-hypnotizables, either during hypnosis or in general, task-relevant posthypnotic suggestions should have no effect on them. This prediction is refuted by the existing evidence (c.f., Zahedi, Sturmer, et al., 2020). Noticeably, newer versions of the metacognitive theory (Lush et al., 2020; Palfi et al., 2020) also advocate that the effects of suggestions are mediated by top-down cognitive processes, which puts the cold control theory at odds with its own basic assumption that the disruption of frontal lobe activity helps or is necessary for responding to suggestions and for modulating the SoA.

2.6. Discrepancy Attribution Theory

Drawing on the selective construction and preservation of experience theory (SCAPE) and its corollary discrepancy attribution hypothesis (Whittlesea, 2002a), Barnier and Mitchell (2005) suggested that these principles can explain hypnotic phenomena (Barnier, Dienes, & Mitchell, 2012). In the SCAPE theory, developed to explain memory processes, Whittlesea (2002a) distinguished between the production processes and their evaluation. Production processes refer to percepts, cognitions, and overt actions. During remembering events, one engages in cognitive and perceptual processing at different levels and simultaneously evaluates these processes. The results of the evaluation can tag a process as coherent, incongruent, or discrepant. The sensation of coherency will arise when all aspects of the current experience are congruent, whereas errors in current processes, that is, when one aspect is incongruent with others, would cause the sensation of incongruity to emerge that will stop the processing. The sensation of discrepancy rises when one aspect of an event is surprisingly fit (or unfit) with other aspects of the event and the source of the surprise cannot be attributed to the event itself. The sensation of discrepancy will cause the agent to search for a plausible source for it, such as past experiences, the agent's current state, or some characteristics of the event. For instance, when participants encounter nonwords constructed by changing one letter of real words, the ease of pronunciation and familiarity of the nonwords is discrepant with their meaninglessness. This discrepancy can be resolved by (falsely) attributing these words to a list of previously encountered words (Whittlesea, 2002a, 2002b), thus creating a false memory. In the false memory literature, the discrepancy hypothesis and SCAPE theory are not prominent, mainly due to their assumption that memory is unitary (Whittlesea, 2002a). Nevertheless, one needs to examine their relevance in explaining hypnotic phenomena, as envisioned by Barnier and Mitchell (2005).

Barnier and Mitchell (2005) assumed that the cognitive and perceptual processes, used to produce responses during hypnosis are the same as those used outside of hypnosis. However, production processes are occurring marginally easier during hypnosis. Since this fluency causes a surprise in hypnotized participants, based on the discrepancy hypothesis, they will falsely attribute this fluency to an implicit characteristic of the event and their own state. In other words, they will attribute the experienced fluency to the involuntariness of their response or being controlled by the hypnotist (Barnier et al., 2012). Why should responses be more fluent during hypnosis? Barnier and Mitchell (2005) suggested that this is due to (1) a positive motivation in participants to be a good subject, and (2) the special characteristics of hypnotic settings, that is, being relaxing and concentration-promoting. Further, the discrepancy attribution theory tries to explain the variance in hypnotizability across participants by assuming that some participants may be either more capable to focus during hypnosis or more sensitive to discrepancy than others. Both cases would promote participants to sense a discrepancy when responding to suggestions and in turn cause them to attribute this discrepancy to involuntariness.

The first question to be asked in evaluating the discrepancy attribution theory is, whether responding to suggestions is indeed more fluent or easier during hypnosis than expected. If so, this expectation cannot come from a comparison between hypnotic versus normal responses, since hypnotic responses are usually characterized by interruption, hesitation, and slowness (e.g., Frith et al., 2000; Martin & Pacherie, 2019). Only if participants would expect to produce no response during hypnosis, producing even a degraded response might be considered as more fluent than expected. However, negative expectations about hypnosis are correlated with lower hypnotizability and unresponsiveness to hypnotic suggestions in general (Green & Lynn, 2011; Jones & Spanos, 1982; Lynn et al., 2019; Lynn et al., 1984). Accordingly, one would expect low-hypnotizables to experience a stronger feeling of fluency and to be more hypnotizable, which is self-contradictory. Second, does hypnotic induction cause more focused attention or self-awareness as Barnier and Mitchell (2005) suggested? According to Terhune and Cardeña (2010), hypnotic induction does not necessarily increase attention or self-awareness. Further, hypnotic suggestions may even trigger contradictory imagination and still bring about the expected responses (Zamansky & Clark, 1986). Noteworthy, attention to behavior usually impairs production processes rather than making them more fluent or easy (Brown et al., 2013; Clark, 2013; Custers & Aarts, 2010). Finally, high-hypnotizables are no different from low-hypnotizables in terms of their attentional capabilities (Dienes et al., 2009) or their sensitivity to discrepancy as evident in their judgments of agency (Terhune & Hedman, 2017). Therefore, it seems that the basic assumptions of the discrepancy theory are questionable.

2.7. Summary and Conclusions

Table 1 presents a summary of the theories reviewed above along with their strengths and weaknesses. In critically reviewing existing theories in the field of hypnosis, it has been shown that many theories cover a certain range of phenomena in the hypnosis domain but do not or only partially account for others. The assumptions of other hypnosis theories, whether borrowed from general cognitive theories or original, are at variance with empirical evidence. One of the most common problems is the concentration of some theories on subjective experiences to the exclusion of observable behavior changes or, conversely, relying exclusively on overt behavior without considering the subjective perspective. Another common issue is that the hypnosis literature has consistently shown that, regardless of the level of difficulty, there are at least three different categories of suggestions (e.g., McConkey et al., 1980; Oakman & Woody, 1996; Piesbergen & Peter, 2006; Woody et al., 2005), but none of the reviewed theories presents a plausible account for the existence of more than two types of suggestions. Probably the most important shortcoming of existing theories, however, is related to their inability to explain performance enhancements in cognitive tasks due to task-relevant hypnotic and posthypnotic suggestions.

The shortcomings of the existing theories of hypnosis prompted us to propose a new theory, taking into account (a) all of the important hypnotic phenomena, including the objective and subjective components, and their neural correlates, (b) individual differences, and (c) current theoretical approaches in neuroscience. In other words, instead of trying to stabilize a pyramid on its apex, we tried to fortify its base.

Table 1. The comparative summary of existing theories of hypnosis with regard to existing observations in the field

Theory	Theoretical Complexity and Consistency [A]	Objective Changes in Perception, Cognition, and Memory [B]				Subjective Alterations in SoA [B]		Hypnotizability [B]		Testable Hypotheses about Neural Underpinnings [C]
		Positive Hallucinations	Negative Hallucinations	Motor Responses	Novel Responses	Involuntariness	Effects of External Factors	Multiple hypnotizability	Multiple Groups of High-Hypnotizables	
Response-Set Theory	4	X	–	X	–	X	X	–	–	No
Neo-Dissociation Theory	5	–	X	X	–	X	–	–	–	No
Dissociation Theory	4	–	(X)	X	–	X	–	–	–	Yes
Decoupling Theory	4	–	–	X	(–)	X	–	–	–	Yes
Unified Cognitive Theory	3	X	–	X	–	X	X	(–)	(–)	No
Interoceptive coding Model	2	(–)	–	X	–	(–)	–	–	–	Yes
New Predictive Coding Model	3	X	–	X	–	X	(X)	–	–	No
Cold Control Theory	4	–	X	X	–	X	X	(–)	–	Yes
Discrepancy Attribution Theory	3	–	–	(X)	–	–	–	(–)	–	No

For detailed descriptions of each phenomenon and theory please see the text. Phenomena [A]: 1: complex and inconsistent – 5: simple and consistent. [B]: X: consistent explanation; (X): (semi-)consistent explanation but not aligned with all existing observations; (–): (semi-)consistent explanation but refuted by existing observation; –: no explanation or severely inconsistent. [C]: Only the existence of testable hypotheses is evaluated, as the interpretation of results can be theoretically biased.

3. Simulation-Adaptation Theory of Hypnosis (SATH)

In this section, we propose a new theory of hypnosis that tries to resolve issues and shortcomings in existing theories. In short, the simulation-adaptation theory (SATH) claims that there are three basic top-down cognitive processes, which can be employed by a cooperative and willing participant in order to successfully exert hypnotic and posthypnotic suggestion-induced responses. Noteworthy, successful exertion of suggestions-induced responses refers to both objective and subjective aspects. These basic top-down processes are (1) *cognitive-simulation* (for review please see Hesslow, 2002): imagining a stimulus, which can lead to perceptual and neural responses similar to experiencing the corresponding stimulus in reality; (2) *sensory-adaptation* (for review please see Frank, 2016; Lopresti-Goodman, Turvey, & Frank, 2013): top-down downregulation of sensory input, which can cause alterations in perception of stimuli, including agnosia; (3) *mental practice* (cf. Zahedi, Sturmer, et al., 2020): mentally simulating a novel situation employed as a practice environment, where new strategies are practiced in order to learn new, context-dependent trigger-response contingencies. These three processes can be employed to different extents and in different combinations, depending on the individual capabilities of the participant.

In the following four sections, we will address how SATH explains hypnosis-related phenomena in three areas. First, we suggest cognitive-simulation and top-down downregulation of sensory input as mechanisms underlying suggestion-induced objective changes in *perception* and the sense of conviction accompanying these changes. Second, we address *overt behavior* triggered by motor suggestions and explain them by combining predictive coding with cognitive-simulation and sensory-adaptation. We also discuss alterations in the subjective SoA during such movements.

Third, we will explain how cognitive-simulation can serve as a sophisticated mental simulator for mentally training skills, which can account for the effects of task-relevant suggestions on *executive functions* both inside and outside of hypnosis. Finally, hypnotic suggestibility and its correlates, such as social, psychological, and cognitive variables are discussed. At the end of each section, we will compare SATH and its conjectures with the theories reviewed in section ***2. Critical Review of Prominent Theories***.

3.1. Changes in Perception

Alterations in perception, induced by suggestions, are commonly called "hallucinations" or "agnosia" to emphasize the strong conviction that participants develop about their imaginations (see ***1.2. Objective Changes in Overt Behavior, Perception, and Cognition***).

3.1.1. Positive Hallucinations are The Direct Result of Imagination

In the most recent version of their theory, Lynn, Laurence, et al. (2015) proposed that hypnosis consists of imaginative suggestions targeting changes in thought, affect, or behavior, a proposition echoing those of others (e.g., Kihlstrom, 2008). In this proposition, the most conspicuous term is *imaginative*. Being imaginative is a common characteristic of all types of hypnotic and posthypnotic suggestions introduced in section ***1.2. Objective Changes in Overt Behavior, Perception, and Cognition***. Even in ideomotor suggestions, where participants shall think about a movement until it transpires (e.g., "think of your head falling forward … and you feel a tendency to make the movement"; Shor & Orne, 1962), imagining the movement is essential. Therefore, there can be little doubt that imagination is, even if not crucial, at least a common characteristic of hypnotic and posthypnotic suggestions. Among the firmest evidence for this proposition is a meta-analysis of neuroimaging studies by Landry et al. (2017), showing that activation of the lingual gyrus is one of the most reliable observations during responding to hypnotic and posthypnotic suggestions. The lingual gyrus is a part of the visual system and critically involved in imagery (Jung, Flores, & Hunter, 2016). Therefore, empirical evidence also highlights the importance of imagery in responding to suggestions of any kind.

The cognitive-simulation theory (for review please see Farah, 1988; Hesslow, 2002) postulates that *imagining* a stimulus is essentially the same as *perceiving* that stimulus, with this difference that during imagery, perception is caused by inner thoughts rather than external stimuli (Fig. 2A). This claim is supported by studies showing that imagining a stimulus not only activates the same brain areas but also causes the same responses as perceiving the corresponding stimulus in reality (for review please see Hesslow, 2002). For instance, the imagination of consuming a particular food, such as cheese, induces habituation (like its actual consumption), and therefore, decreases the tendency of participants to consume this kind of food (Morewedge, Huh, & Vosgerau, 2010). Further, imagining performing an action will activate the same premotor and supplementary motor cortices as executing that action; the only difference is that the imaginary action does not activate the primary motor cortex, at least not as strongly as executing the action (for review please see Hesslow, 2002).

What is the relation between cognitive-simulation and the effects of suggestions? As discussed above, imagination is an indispensable element of all suggestions. Therefore, when a participant is suggested to see, hear, or imagine a stimulus, it essentially induces cognitive-simulation of that stimulus. Hence, one should expect that suggestions trigger the same (perceptual and neural) effects as perceiving the corresponding stimuli. Supporting this claim, when different forms of positive hallucinations induced by suggestions are considered, such as auditory (e.g., Szechtman, Woody, Bowers, & Nahmias, 1998; Woody & Szechtman, 2000), visual (e.g., Mazzoni et al., 2009; McGeown et al., 2012), and tactile hallucinations (e.g., Derbyshire et al., 2004), they cause the activation of the same brain regions as perceiving the corresponding stimuli in reality. For instance, in an fMRI study, McGeown et al. (2012) first showed a grey scale and a color scale to their participants (Fig. 2B); later, they showed the grey scale and suggested to participants to mentally add color to the scale, either inside or outside of hypnosis. Regardless of hypnosis, in high-hypnotic-suggestibles, the suggestion induced the imagery of color, which was correlated with activity in color-sensitive brain areas (Fig. 2C). Other fMRI recordings by Derbyshire et al. (2004) revealed that hypnotic suggestion-induced pain and pain caused by physical stimuli activated similar brain areas, including the thalamus, ACC, insula, prefrontal, and parietal cortices (Fig. 2D).

Another argument advocating that positive hallucinations can be explained by cognitive-simulation is that many studies showed that effects of hypnotic and posthypnotic suggestions are similar to the same suggestions outside of hypnosis, in terms of both performance and brain activity (e.g., Mazzoni et al., 2009; McGeown et al., 2012; Palfi et al., 2020; Parris & Dienes, 2013). This finding, besides the fact that suggestions outside of hypnosis closely resemble normal imaginative experiences, supports the idea that positive hallucinations are closely related to imagination and cognitive-simulation.

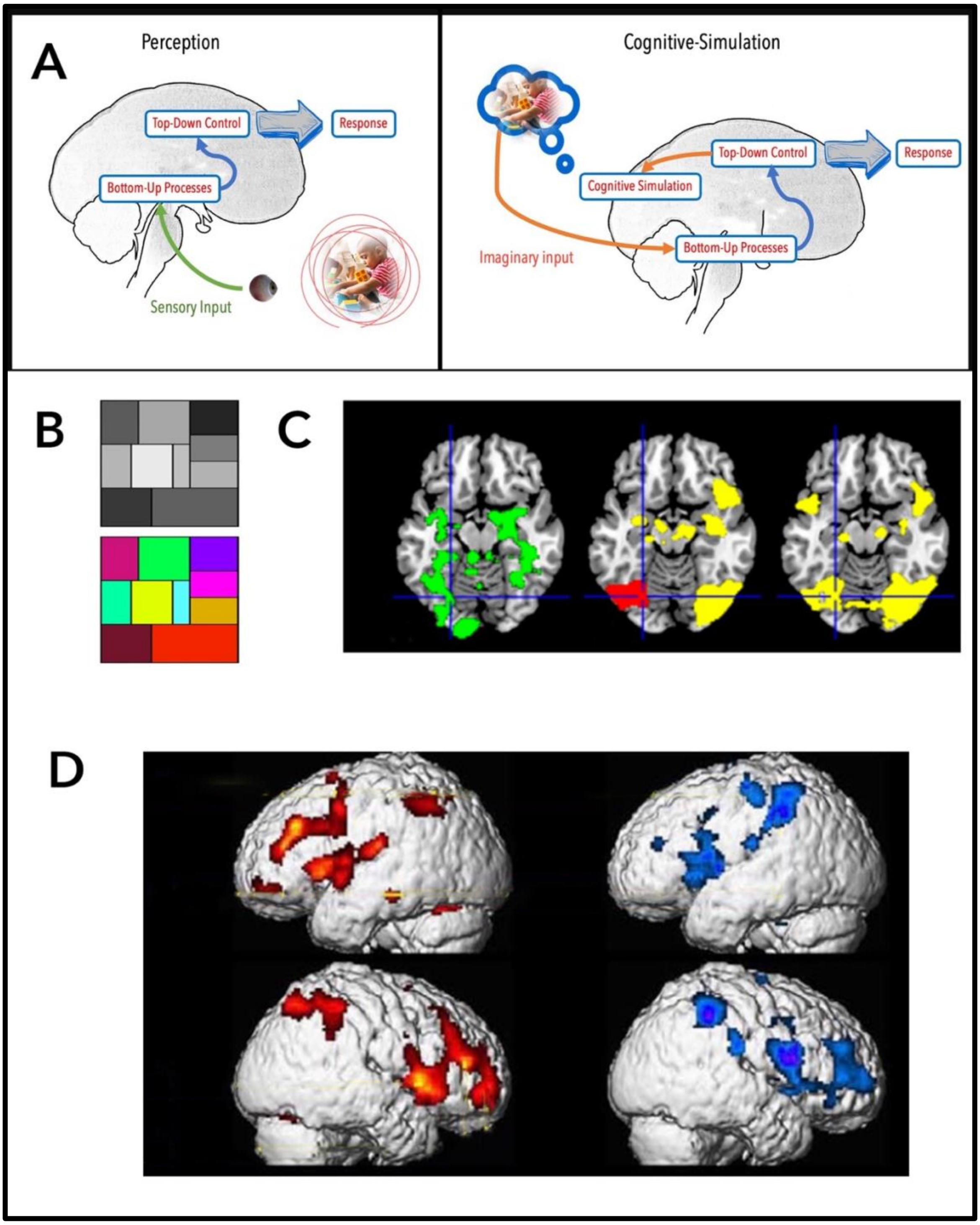


Figure 2. A) The schematic representation of Stimulus-Response association during perception of a stimulus in (left) the real world and (right) cognitive-simulation of the same stimulus. B) color and grey scales used in the study of McGeown et al. (2012). C) (left) the pattern of activation when viewing colors- compared to greyscales; (middle) effects of a suggestion inducing positive color hallucination when looking at the grey scale in high-hypnotic-suggestibles without hypnotic induction, (right) and high-hypnotic-suggestibles with hypnotic induction; Crosshairs: the left fusiform region (B and C reproduced with permission from McGeown et al., 2012). D) Brain activity of physically induced pain (left, red-yellow scale) and hypnotically induced pain (right, blue-purple scale) (adapted with permission from Derbyshire et al., 2004).

Nevertheless, two controversial studies should be discussed. First, Szechtman et al. (1998) tried to show that hypnotic suggestions and imagination affect hypnotized participants differently. They reported that in hypnotized participants, listening to a real sound and the hypnotic suggestion that a sound is present (their "hallucination condition") lead to vivid impressions of hearing a sound. However, a hypnotic suggestion to "imagine" the sound did not cause the same report. Positron emission tomography (PET) imaging showed that the hallucination and real sound condition activated both the auditory temporal cortex and the ACC, whereas the imagination suggestion only activated the temporal cortex but not the ACC. Hence, one might question whether imagination is really similar to positive hallucinations caused by hypnotic suggestions. One should point out that in the study of Szechtman et al. (1998) all three conditions took place inside of hypnosis and, hence, were induced by hypnotic suggestions. Therefore, differences between these conditions cannot be used to address the differences between imagination (without hypnosis) and hypnotic suggestions. In this special study, by contrasting different conditions, participants might have developed the hypothesis that the imagination condition should be less severe than the hallucination or listening conditions. The same concern may apply to the study of Derbyshire et al. (2004), which used the method of Szechtman et al. (1998) and compared the effects of a physically painful stimulus, the imagination of pain, and hypnotic suggestion-induced pain.

In another study, Zamansky and Clark (1986) gave contradictory suggestions ("involved imagery") to participants, while they responded to direct (target) suggestions of the hypnotist. For instance, while participants were responding to the (target) suggestion to bend their (right) arm, the hypnotist asked them to imagine not being able to bend their arm. Interestingly, contradictory-to-direct suggestions did not prevent medium- and high-hypnotic-suggestible participants from following target suggestions (i.e., not performing the movement). In other words, participants produced the same response as when receiving only direct suggestions. When considering the results of Zamansky and Clark (1986), it should be noticed that contradictory suggestions were presented, only if, and immediately after hypnotized participants had successfully responded to the only-direct-suggestion condition. Consequently, the participants' response to the second suggestion (with contradiction) may have been based on the hypothesis that these contradictory suggestions should be resisted. This idea is supported by studies of Spanos et al. (1985) and Lynn et al. (1984), where two groups of high-hypnotizable participants were to resist hypnotic suggestions; one group was informed before hypnosis that good subjects cannot resist suggestions and the other group was informed to the contrary. Interestingly, the latter but not the former group could resist the suggestions. These findings indicate that being able to resist a suggestion greatly depends on the expectations of the participants.

3.1.2 Negative Hallucinations are Related to Sensory-Adaptation

Cognitive-simulation might explain positive hallucinations, but not negative hallucinations, such as pain-reducing suggestions or the "three boxes" suggestion in the Sandford hypnotic susceptibility scale, where three boxes are placed in front of participants but the hypnotist informs them that there are only two (Weitzenhoffer & Hilgard, 1962). In this section, we focus on pain-reducing suggestions, as they are successful in a majority of participants and there is ample evidence about their neural underpinnings (for review please see Thompson et al., 2019).

For understanding negative hallucinations, the concept of negative hysteresis (Frank, 2016) and how it relates to top-down processes is of great importance. A good example of negative hysteresis is provided by Lopresti-Goodman et al. (2013); they asked two groups of participants to judge whether they needed one or two hands to grasp wooden planks of different sizes. Participants in the control group actually grasped the planks, whereas the experimental participants merely saw the planks but were not allowed to touch them. Instead, participants in the experimental condition verbally reported whether they would need one or two hands. Importantly, planks were presented one by one in both ascending and descending size-orders. In the control group the plank size, at which participants changed from one to two hands or vice versa was slightly (but non-significantly) larger for ascending than descending presentation order (positive hysteresis). In contrast, in the experimental group without physical contact with the planks, the change point was situated at a considerably smaller size in the ascending than in the descending order, that is, participants showed negative hysteresis. Frank (2016) explained this phenomenon in the framework of a Lotka–Volterra–Haken model for two neural populations representing the alternative responses in the task: (A1) a one-hand population and (A2) a two-hand population. In the control group, which actually executed the grasps and showed positive hysteresis, the outcome was modeled as:

$$\frac{d}{dt}A_1 = \alpha_1 A_1 - A_1^d - \beta\, A_2^{d-1}\, A_1;\ \frac{d}{dt}A_2 = \alpha_2 A_2 - A_2^d - \beta\, A_1^{d-1}\, A_2. \quad (1)$$

where, α_1, α_2, and β represent synaptic weights of intra- and inter-population connections; α_1 and α_2 are exponential growth factors describing the increase or decay of the population variables in the linear format, and β designates the inhibitory interaction between the populations; d captures nonlinearities in the system.

To account for negative hysteresis, observed in the experimental group of Lopresti-Goodman et al. (2013), the activities of the neural populations must be adapted due to the prolonged neural activity (Frank, 2016; Lopresti-Goodman et al., 2013). Here, α_1 and α_2 vary slowly across each repetition of perception as follows:

$$\begin{cases}\alpha_1 = L_1(n) - \gamma \\ \alpha_2 = L_2(n) + \gamma\end{cases};$$

$$i = 1,2, and\ \forall\, T > 1;\ \ L_i(n) = L_i(n-1) - \frac{1}{T}((L_i(n-1) - (L_{i,0} - s_i)). \quad (2)$$

where γ designates the variable of interest in relative format (e.g., relative plank size), L_1 and L_2 denote the dynamic rest levels of growth parameters α_1 and α_2, respectively. Further, $L_{1,0}$, $L_{2,0}$, s_1, and s_2 define the resting levels after adaptation is completed (L_1 and L_2), as determined by theoretical considerations and experimental observations, respectively. Finally, T denotes the time scale of adaptation (for further mathematical details please see Lopresti-Goodman et al., 2013).

By combining Equations 1 and 2, negative hysteresis can be explained in terms of downregulation of neural activity of the targeted population due to prolonged neural activity. In ascending order, the one-hand population increasingly adapts across repetitions and is dominated by the two-hand population at a plank size smaller than in the physical perception condition. Conversely, in descending order, the two-hand population adapts across repetitions. This opposite shift in the change points yields negative hysteresis. Why is prolonged neural activity relevant only for the experimental condition? In the experimental condition, participants form mental representations of perceived objects, maintain them in their working memory, and examine (manipulate) them to judge how they should be grasped. In contrast, controls respond directly to their perceptions, and therefore, perceived stimuli will not be transmitted into working memory. Hence, downregulation of the adapting neural population is conceived as a top-down process, as it is related to attention allocation rather than to a disturbance in bottom-up processes. The idea that top-down processes regulate perception and can directly affect perceptual pathways starting from thalamic activities is not restricted to negative hysteresis and has been corroborated by many studies (for review please see Saalmann & Kastner, 2009), and even in non-human subjects (Manita et al., 2015). However, the focus of negative hysteresis on prolonged neural activity caused by imagination (and not by physical sensation) is integral to understanding the effects of suggestions.

How can sensory-adaptation help us to understand negative hallucinations? Let's focus on pain reduction as a common example of negative hallucinations. There are innumerable pain-reducing suggestions (for review please see Hammond, 1998) but most ask participants to form a mental representation of pain eliciting stimuli and to manipulate this mental representation. For instance, participants might be asked to describe pain elicited by noxious stimuli in terms of a physical object (e.g., a balloon or bricks), and interact with this object (e.g., crunch it or reduce its size). Therefore, in contrast to normal conditions, where participants directly react to stimuli, suggestions ask them to form a mental representation of noxious stimuli, similar to the experimental group of Lopresti-Goodman et al. (2013).

Let's assume that there are two neural populations with growth parameters α_1 and α_2, where the activation of one population classifies a stimulus, such as an ice cube on the skin, as harmless whereas the other population classifies it as painfully cold. In normal situations with direct reactions to pain-evoking stimuli, Equation 1 only explains positive hysteresis. That is, when a stimulus is already judged as painful, the stimulus will be judged as non-painful somewhat even below the threshold for an isolated stimulus. Conversely, when reacting to the same stimulus after a pain-reducing hypnotic suggestion, the fact that participants form a mental representation of the stimulus and work on it (e.g., by judging its severity or trying to describe and manipulate it) will cause a prolonged neural activity in the pain perception population. Therefore, the growth parameter of the pain perception population, α_2, will be downregulated, as described in Equation 2. Consequently, the critical value, at which participants judge stimuli as non-painful, will be increased (negative hysteresis) and the same stimulus can be perceived as harmless much sooner than in normal conditions. In other words, suggestions reduce pain by establishing a mental representation of pain, causing a prolonged neural activity, that results in sensory-adaptation. This mechanism is not restricted to pain-provoking stimuli, but the perception of any stimulus, such as tactile non-pain provoking stimuli, can be affected by sensory downregulation (via top-down processes) when participants form a mental representation of the stimulus and engage in manipulating this representation (e.g., Vanhaudenhuyse et al., 2009).

The adaptation account of negative hallucinations predicts that brain areas, being activated in response to noxious stimuli, will be less activated after receiving pain-reduction suggestions in comparison to normal conditions. This prediction is supported by both fMRI and ERP studies. For instance, in an fMRI study, Vanhaudenhuyse et al. (2009) found that all brain regions activated by pain perception, that is, brainstem, right thalamus, bilateral striatum, right primary somatosensory, bilateral insula, anterior cingulate cortex, right middle frontal gyrus, and right premotor cortex, showed less activation following pain-reducing hypnotic suggestions in comparison to a normal condition without hypnosis (Fig, 3A). In an ERP study, Perri et al. (2019) found hypnotic suggestions to reduce ERP components correlated with pain perception, such as N20, P100, P150, and P250 (Fig. 3B). Therefore, the top-down sensory downregulation of the neural population responsible for judging and labeling stimuli as painful may explain pain reduction due to hypnotic suggestions. Reasonably, sensory adaption processes may also explain other negative hallucinations.

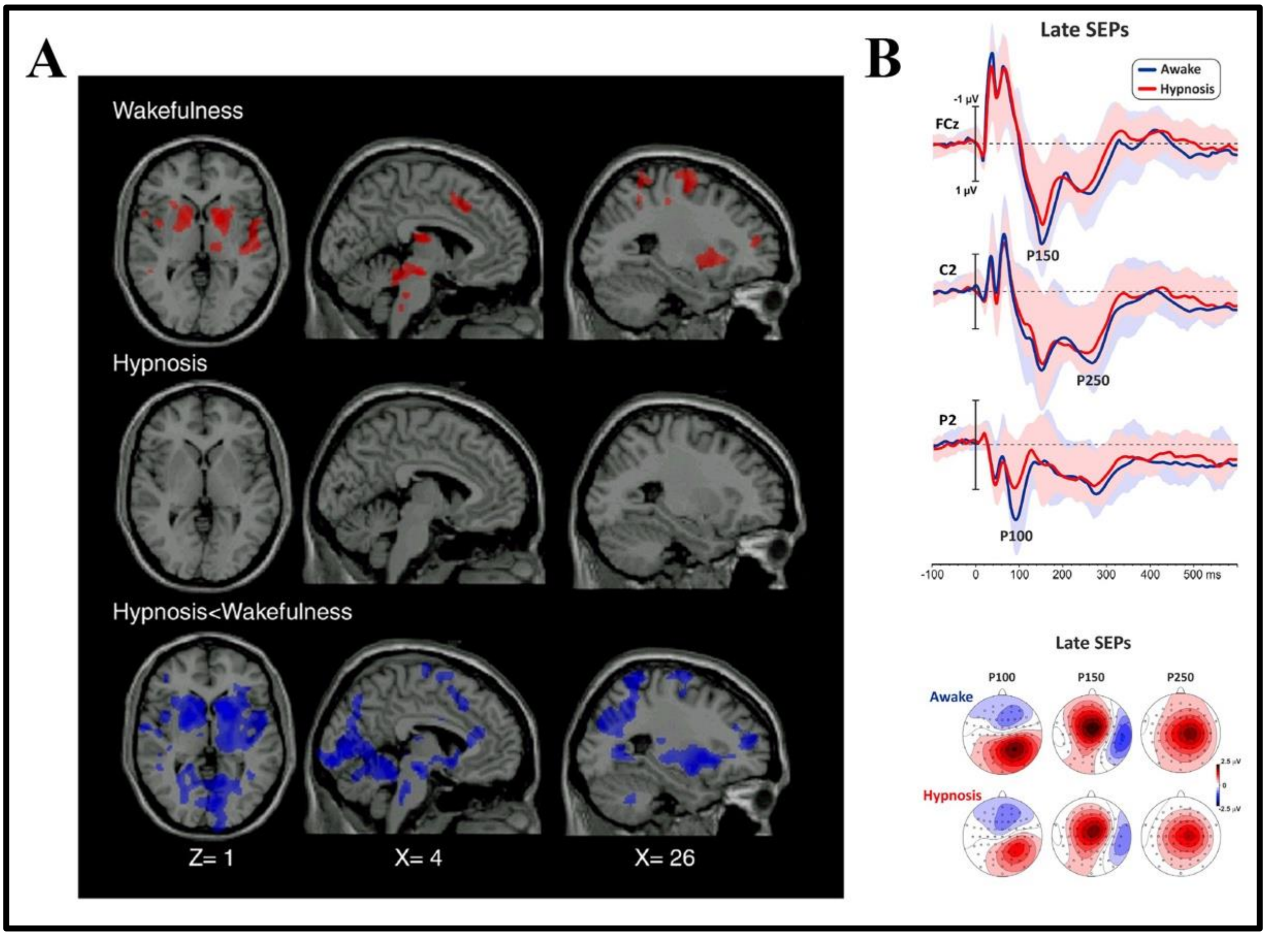


Figure 3. Decrease in brain activity after pain-reducing hypnotic suggestions; A) brain regions showing significant ($p<0.05$) activation during noxious stimulation (upper row) without hypnosis, (middle row) under the influence of pain-reducing hypnotic suggestions, and (lower row) the hypnotic condition minus the no-hypnosis condition (adapted with permission from Vanhaudenhuyse et al., 2009). B) (top) grand-average waveforms of sensory-evoked potentials (SEPs) without hypnosis and during hypnosis; shaded areas are representing standard deviations; (bottom) topographic maps of the P100, P150, and P250 components in the two conditions (adapted with permission from Perri et al., 2019).

3.1.3. Sense of Conviction

Why do participants develop a sense of conviction only in response to suggestions but not during normal imagination? Ganis and Schendan (2008) compared ERP effects of imagining stimuli with perceiving them and showed that imaginations induced the same perceptual processes as external stimuli. The authors discussed that mental imagery caused mental representations of imagined stimuli to be formed and maintained in working memory. This was in contrast to the perception condition, where perceptual representations were quickly discarded through bottom-up decay. Ganis and Schendan (2008) concluded that due to the difference in the persistence of (mental vs. perceptual) representations, participants usually do not confuse mental imagery with the perception of external stimuli. Let's consider the effects of suggestions. During positive hallucinations, participants are asked to form a stream of mental images (e.g., a developing story rather than a single image). Therefore, participants are not forming just a single mental representation but a stream of representations, which is subjected to the same normal bottom-up decay as external stimuli, as they are not maintained in working memory, but discarded immediately (the distinguishing property of perceptual representations). Therefore, these representations are easy to be confused with perceived real-life events. During negative hallucinations, however, an external stimulus is transformed into a mental representation and manipulated repeatedly, causing a prolonged neural activation that can be subjected to top-down sensory-adaptation. Therefore, when participants respond successfully to perception-related suggestions, the subjective sense of conviction about the mental imagery seems to be a byproduct of the underlying cognitive processes rather than related to participants' expectations or post hoc interpretations.

3.1.4. Comparison with Other Theories

How does SATH compare with other theories? First, SATH and the response-set theory (reviewed in section ***2.1. Response-Set Theory and Integrative Model***) are similar with regard to emphasizing imagination as the underlying mechanism for some of the objective changes in perception. However, SATH proposes top-down sensory-adaptation as a second mechanism, in order to explain negative hallucinations, which are not accounted for by the response-set theory. Further, in contrast to the response-set theory, SATH does not attribute the perceptual effects of suggestions to automatic response activation, but to two top-down processes, that is, cognitive-simulation and sensory-adaptation. Finally, although social and psychological variables are most likely important for implementing and facilitating suggestions, they are probably insufficient to account for the observed effects and must be distinguished from the mechanisms underlying the effects of suggestions.

Second, dissociation theories (reviewed in section ***2.2. Dissociation and Decoupling Theories***) can be easily distinguished from SATH, which assumes several top-down processes as mechanisms underlying the perceptual effects of suggestions. In contrast, dissociation theory attributes these effects to disruption of some top-down processes, such as error monitoring. The advantage of SATH is its capability to understand positive and negative hallucinations at a mechanistic level, which is not the case for dissociation theories.

Third, in contrast to the cold control theory (reviewed in section ***2.5. Cold Control Theory***), SATH does not assume that blocking higher-order thoughts is responsible for objective changes in overt behavior and perception. To the contrary, SATH proposes that negative hallucinations are caused by forming and maintaining mental representations of external stimuli that results in top-down-driven downregulation of the external input. Further, in contrast to SATH, the cold control theory cannot explain positive hallucinations.

3.2. Motor Suggestions

After accounting for perceptual hypnotic phenomena, we now turn to effects of motor suggestions (reviewed in section ***1.2. Objective Changes in Overt Behavior, Perception, and Cognition***). Cognitive-simulation and its more specific counterpart for motor responses, the ideomotor mechanism, have problems explaining the observed effects of suggestions as stand-alone mechanisms. The ideomotor theory (for review please see Shin, Proctor, & Capaldi, 2010), especially the theory of event coding (TEC) (Hommel, Musseler, Aschersleben, & Prinz, 2001), states that thinking of the (perceptual) effects of a physical movement, which are retained and internalized through repetitions, will induce a tendency to produce that movement. For instance, in the study of Elsner and Hommel (2001) participants repeatedly experienced a fixed co-occurrence between right and left button presses and low- and high-pitched tones during the training phase. In the following test phase, low- and high-pitched tones preceded responses. The results indicated that the effects of a response (low and high tones) can activate the corresponding right and left button presses. Follow-up neuroimaging studies showed that response activations were correlated with activation of (predominantly left) premotor and somatosensory cortices (e.g., Melcher, Weidema, Eenshuistra, Hommel, & Gruber, 2008; Melcher et al., 2013). However, this tendency by itself rarely caused a full-fledged movement, at variance with motor suggestions during hypnosis, which in most participants successfully induce complete movements (Shor & Orne, 1963; Woody et al., 2005).

When comparing the cognitive-simulation with the ideomotor theory, one should notice that in cognitive-simulation, it is assumed that if an unconditioned stimulus (e.g., the buoyancy of a helium-filled balloon) has been repeatedly experienced and caused an unconditioned response (e.g., raising hands), the *imagination* of the stimulus (presumably a conditioned stimulus) can induce a tendency to perform a conditioned response similar to the unconditioned response. Therefore, $CS \rightarrow CR$. Ideomotor theory (Elsner & Hommel, 2001), on the other hand, assumes that if an action (e.g. a button press) had been exerted repeatedly and caused an effect (E) (e.g., a high-pitched sound), the perception of the effect can induce a tendency to perform the action (e.g. pressing a button), therefore, $E \rightarrow CR$. However, also in ideomotor theory, it seems that effects of actions are becoming conditioned stimuli. Consequently, when we discuss motor suggestions, both forms of suggestions, that is, the suggestion to think about a movement ($E \rightarrow CR$) or about a movement-associated stimulus ($CS \rightarrow CR$), will be treated similarly and are assumed to be governed by similar principles.

Based on the predictive coding model (see section ***2.4. Predictive Coding Models***), a voluntary motor response is initiated by forming a prediction, which is propagated downward in cortico-cortical and corticospinal projections till it reaches the targeted muscles. During active inference (related to volitional movements) (Fig. 1), somatosensory feedback is used to form prediction errors. Even though back-propagation of prediction errors is used to correct movements (if they are not aligned with predictions), prediction errors are gradually downregulated in reflex arcs and blocked completely beyond thalamic nuclei (Adams et al., 2013; Brown et al., 2013). Therefore, during active inference, somatosensory feedback is only used to correct movements but not to update predictions.

SATH combines cognitive-simulation, sensory-adaptation, and predictive coding, in order to explain the effects of motor suggestions. Let's consider a common motor suggestion (Fig. 4A), where participants imagine helium-filled balloons attached to their hands, and simultaneously, are asked to concentrate on sensations coming from the targeted hand or on changes in these sensations, such as, temperature, comfort, and so forth, which commonly facilitates the hypnotic suggestion-induced action. After receiving this suggestion, according to the cognitive-simulation mechanism (section ***3.1.1. Positive Hallucinations are The Direct Result of Imagination***), a second source of input will be generated (i.e., a positive hallucination). Hence, two sources of input are available, (I) somatosensory and proprioceptive input from external sources and from the participants' body, and (II) input from conditioned stimuli coming from imagination. According to sensory-adaptation (section ***3.1.2 Negative Hallucinations are Related to Sensory-Adaptation***), if two neural populations, corresponding to these two sources of input, with growth factors α_1 and α_2, respectively, compete for dominance, they will be governed by the mechanisms described in Equations 1 and 2. Therefore, when participants form a mental representation of their hand, sensory-adaptation will downregulate the growth factor of the neural population corresponding to somatosensory and proprioceptive input. It is plausible that hypnotizable participants will form predictions based on their imaginations that an external force (e.g., balloons) buoys their hand upward. However, until the somatosensory input is downregulated severely, there would be a precise prediction error that will prevent any movement. As soon as α_1 is downregulated enough to judge the second source of input (imaginary input) as dominant, the prediction errors vanish, and the upward movement will start. Noticeably, as the downregulation of somatosensory input transpires through top-down rather than bottom-up processes, somatosensory input will be used in reflex arcs for guiding the movement in the predicted direction.

Five questions remain to be addressed. (1) Can SATH explain why movements occur during motor suggestions? Two pillars of predictive coding should be noticed. (I) Down-propagating signals through cortico-cortical and corticospinal projections are predictions and not motor commands (Adams et al., 2013). (II) Two forms of inference exist (Fig. 1A, B), namely active and perceptual movement. Active inference brings about the execution of movements and perceptual inference results in the perception of stimuli (e.g., externally driven movements). The main difference between the two forms of inference is that during active inference predictions are more precise (i.e., have higher weights in the system) than prediction errors, since prediction errors (sensory feedback) are "attenuated" (used only in reflex arcs for aligning the movement with predictions). In contrast, during perceptual inference prediction errors are more precise than predictions, causing predictions to be updated according to somatosensory feedback, which results in perceiving sensations during an (externally driven) movement without executing any movement

(Brown et al., 2013; Clark, 2013). Therefore, for a movement to occur, two elements are necessary, the down-propagation of predictions and the attenuation of sensory feedback. These two elements together enforce the predicted movement to occur, instead of updating predictions based on sensory feedback (Brown et al., 2013). SATH involves both elements, *down-propagating predictions* based on mental imagery, and *down-regulating sensory feedback* due to prolonged activation through top-down sensory-adaptation.

(2) What are the differences between normal movements and those induced by hypnotic suggestions, and can these differences predict alterations in the subjective SoA? If we consider the proposition of SATH for hypnotic-suggestion-induced movements, there are two elements. (I) Predictions, generated based on imagined stimuli, are more precise in comparison to somatosensory feedback, which is downregulated by sensory-adaptation (imitating active inference). However, (II) predictions are less precise in comparison to feedback from imaginations and, therefore, predictions are being updated to be congruent with feedback from mental imagery (similar to perpetual inference). In this structure, movements occur since predictions are more precise than somatosensory feedback. Nevertheless, as predictions are being updated based on imaginary somatosensory feedback, participants' judgment about the movement will be similar to perceptual inference. That is, they will not appraise their movements as being goal-directed but will develop the conviction that the movements are attributable to external forces rather than to themselves. This is in contrast to normal goal-directed, volitional movements (active inference), during which predictions are not updated because no significant prediction error is engendered. That is, in normal active inference sensory feedback is attenuated before it reaches thalamic gates and there is no second source of input, such as imaginary sensory feedback. Therefore, during normal active inference the movement is judged as volitional (Brown et al., 2013), in contrast to

hypnotic-suggestion-induced responses. This prediction of SATH can interpret the common definition of “non-voluntariness” during hypnosis by Lynn et al. (1990) and “sense of conviction” discussed by Kihlstrom (2008), which was discussed in section ***1.3. Alterations in the Subjective Sense of Agency.***

SATH proposes that somatosensory feedback is downregulated due to repeated perception (prolonged neural activity), which is a slower process in comparison to sensory attenuation. Therefore, cerebral and thalamic activities should be higher under the influence of motor suggestions in comparison to normal movements (where somatosensory feedback is attenuated from the beginning), as was indeed observed in fMRI recordings by Blakemore et al. (2003) (Fig. 4B). Also, the brain regions related to imagery, such as the precuneus, extrastriata visual areas (Cojan et al., 2009), and frontal regions (especially dorsolateral prefrontal cortex), should be more active during suggestion-induced than voluntary movements, which was confirmed by Cojan et al. (2009); (Ludwig et al., 2015), and these imagery related areas should have stronger functional connectivity with frontal regions, as observed by Pyka et al. (2011). Furthermore, due to the postulated downregulation of somatosensory feedback, it is reasonable that during suggestion-induced movements, the activation of somatosensory cortices was found to be less salient and less connected with frontal and motor areas (Deeley et al., 2013; Walsh et al., 2015).

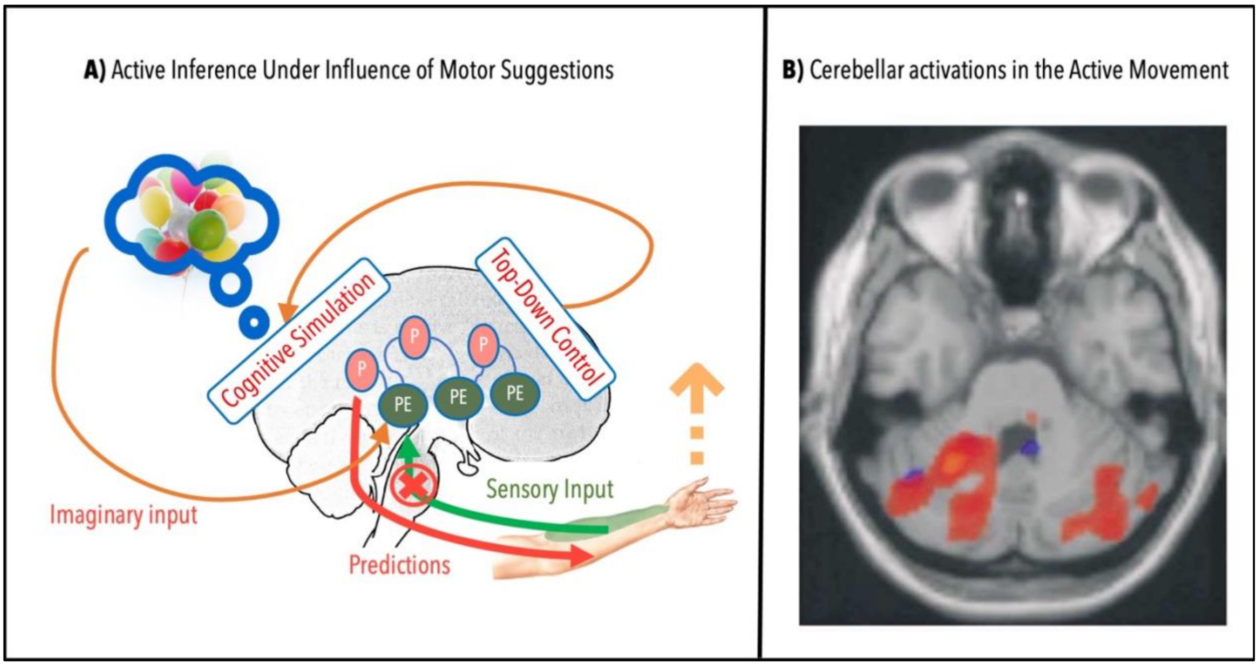


Figure 4. A) The schematic representation of motor suggestions; P: predictions, PE: prediction errors. For a detailed explanation of processes please look at the text. B) Cerebellar activations in the Active Movement (blue) and Deluded Passive Movement (red) conditions. Activations in the cerebellum are more widespread in the Deluded Passive Movement condition compared with the Active Movement condition (adapted with permission from Blakemore et al., 2003).

(3) Why are hypnotic-suggestion-induced movements typically interrupted, hesitant, and slow (e.g., Frith et al., 2000; Martin & Pacherie, 2019)? This can be explained by the processes proposed by SATH. Since the initiation of hypnotic-suggestion-induced movements requires the downregulation of somatosensory feedback, movement-onset will be delayed until prolonged neural activity drives the downregulation of sensory input to the point that predictions are more precise than somatosensory signals. Once initiated, a movement accelerates and continues if the participant remains concentrated on the process and is not distracted. Based on Equation 2, distraction reverses the downregulation of the growth factor α_1 and the participant needs to refocus on the sensations coming from the targeted limb for some time until downregulation again reaches the point where the movement restarts.

(4) Why are some suggestions easier to follow than others? Some motor suggestions, in particular, ideomotor suggestions (to be distinguished from the ideomotor theory) are more easily responded to than so-called challenge suggestions (McConkey et al., 1980; Woody et al., 2005). A typical ideomotor suggestion is the hand lowering suggestion: “stretch your left arm and after a while, you feel tiredness in your arm and hand, and they start to lower” (Shor & Orne, 1962). Conspicuously, in ideomotor suggestions, somatosensory input and imagery input are congruent, and therefore, negative hallucinations are not necessary to start or execute the movement. To the contrary, in challenge suggestions, such as hand levitation (discussed above), somatosensory input is incongruent with imagery input and, therefore, the movement will start and proceed only if negative hallucinations occur first. This also explains why these two forms of motor suggestions load on different factors when hypnotizability scales are submitted to factor analysis (McConkey et al., 1980; Woody et al., 2005).

(5) How does SATH explain that participants can use different strategies to implement suggestions? In section ***2.4.2. New Predictive Coding Model***, we discussed the study of Galea et al. (2010), which demonstrated that participants can use different strategies to implement the same motor suggestion. This observation aligns with SATH. If suggestions are ambiguous about the imagery to be used (CS), participants are likely to come up with their own. These imaginations may differ, and therefore, have different consequences (CR). For instance, in the study of Galea et al. (2010), participants were suggested to imagine being unable to move their arms. If participants imagine that their arms are locked, they may activate the targeted muscle group but simultaneously block the movement by activating the opponent muscles; but if they imagine that their arms are temporarily paralyzed, they may only activate the opponent muscles, or do not activate any muscle at all. Neuroimaging data supporting this suggestion have been reported by Deeley et al. (2014).

They reported that different (precise and elaborated) motor suggestions, focusing on a similar movement but consisting of different imaginations (CS), caused different patterns of activation and functional brain connectivity (CR). These results show the neural correlates of suggestions depend on which mental imagery and strategy they are presenting. Hence, if participants imagine different stimuli, their CRs will also differ.

3.2.1. Comparison with Other Theories

In contrast to the interoceptive predicting coding theory (reviewed in section ***2.4.1. Interoceptive Predictive Coding***), SATH assumes that the same networks underlying normal actions are also driving actions induced by hypnotic suggestions. And in contrast to the new predictive coding model (reviewed in section ***2.4.2. New Predictive Coding Model***), SATH does not expect that unresolved prediction errors cause participants to attribute their actions to external sources. Instead, SATH assumes that prediction errors are resolved by updating predictions based on imaginary somatosensory feedback. That is, on one hand, predictions are more precise (have a higher weight in the system) than somatosensory input, causing the overt action to be initiated. On the other hand, predictions are less precise than imaginary somatosensory feedback, causing predictions to be updated based on the imaginary input. Noteworthy, participants ground their judgment of agency on these new predictions, that is, external sources are seen behind their actions. Based on the proposed structure SATH, one can explain why participants may use different strategies, which cannot be explained by the two alternative theories discussed here.

Further, in contrast to the discrepancy attribution theory (reviewed in section ***2.6. Discrepancy Attribution Theory***), which assumes that the excessive fluency of actions under the influence of hypnosis may lead participants to judge their behavior as externally controlled, SATH holds that somatosensory adaptation causes disfluency in suggestion-induced behavior. This assumption is corroborated by empirical findings (e.g., Frith et al., 2000; Martin & Pacherie, 2019).

3.3. Learning and Other Cognitive Changes

3.3.1. Effects of Suggestion on Executive Functions

An important type of objective changes discussed in section ***1.2. Objective Changes in Overt Behavior, Perception, and Cognition*** are related to the suppression of habitual responses or to learning new trigger-response contingencies. Here we will first discuss how SATH accounts for the effects of task-relevant suggestions on performance in cognitive tasks, followed by the effects of neutral hypnosis (i.e., hypnosis without task-relevant suggestion). Briefly, SATH claims that the enhancing effects of suggestions on performing cognitive tasks can be attributed to improved learning of new trigger-response contingencies and, consequently, more efficient implementation of cognitive control processes.

Many studies using posthypnotic suggestions to manipulate cognitive processes have focused on the inhibition function as required, for example, in the Stroop (Raz et al., 2006; Zahedi et al., 2019), Erikson (Iani et al., 2006), Simon (Iani et al., 2009), and Go-NoGo task (Zahedi, Luczak, et al., 2020). In these tasks, performance enhancements can be attributed to both bottom-up or top-down processes (cf. Zahedi, Sturmer, et al., 2020). For instance, in the Stroop task, color words, written in different ink colors, are presented and participants are required to respond to the ink colors while ignoring word meaning. Here, a habitual response, that is, reading the word, has to be suppressed in order to avoid conflicts with naming the ink color. Consequently, one can infer that better Stroop task performance is related to (1) alterations in bottom-up processes, for instance, blocking interfering semantic input to prevent conflicts. To understand the bottom-up account in the Stroop task one may consider a special form of dyslexia, characterized by letter-by-letter reading, which is caused by damage to the occipitotemporal region of the left hemisphere through which visual word-forms are attained (Warrington & Shallice, 1980). In the same manner, if posthypnotic suggestions in the Stroop task can affect bottom-up processes, for instance, by decoupling or impairing the word-form system, task performance will be enhanced without employing cognitive control. Alternatively, (2) participants may deploy additional top-down cognitive control to detect and suppress interfering information more efficiently, which, in turn, facilitates conflict resolution.

Recent findings show that posthypnotic suggestions can also enhance performance in working memory updating tasks (Lindelov et al., 2017; Zahedi, Sturmer, et al., 2020), where changes in bottom-up processes cannot contribute significantly to task performance enhancements (cf. Zahedi, Sturmer, et al., 2020). Therefore, the effects of hypnotic and posthypnotic suggestions may be specifically related to alterations in top-down processes (Terhune et al., 2017). But, which specific top-down processes can be affected by posthypnotic suggestions, is a more contentious issue.

Usually, hypnotic and posthypnotic suggestions, which are used to improve performance in cognitive tasks, are merely elaborated rephrasings of task instructions, and therefore, their effects cannot be attributed to the implementation of a different strategy (Zahedi, Sturmer, et al., 2020). However, when one considers cognitive tasks in general, they obviously engage participants in novel situations requiring the development of new responses. These new responses may consist of, (I) substituting habitual, prepotent responses with a novel trigger-response contingency (e.g., in inhibition tasks) or (II) developing a new response, as in updating tasks. Also, in many of these studies hypnotized participants are asked to imagine the targeted task and implement suggestions in their imagination (Zahedi et al., 2017; Zahedi, Sturmer, et al., 2020). Therefore, cognitive-simulation (see ***3.1.1. Positive Hallucinations are The Direct Result of Imagination***) provides a ground for mental training, during which an appropriate, novel response based on the presented cognitive strategy will be mentally practiced. In case that no strategy has been given, an additional step is required, that is, finding an applicable cognitive strategy. Mental practice makes participants capable to learn trigger-action contingencies and to reinforce them until they can be efficiently used. Noticeably, it has been shown that independent of hypnotic suggestions, the application of mental practice can enhance physical or cognitive skill-learning-procedures (e.g., Frank, Land, & Schack, 2015; Stefanidis et al., 2017). Further, refuting the claim that only hypnotic and posthypnotic suggestions can affect performance, it has been shown that task-relevant suggestions can enhance cognitive performance also outside of hypnosis (e.g., Palfi et al., 2020; Parris & Dienes, 2013).

Can the learning of a new trigger-response contingency boost performance in both inhibition and updating tasks? In inhibition tasks, a second well-learned trigger-action association, which can compete with the automatic but inappropriate response, makes participants capable to exert inhibition more efficiently and, therefore, enhances performance (e.g., Dulaney & Rogers, 1994; Protopapas, Vlahou, Moirou, & Ziaka, 2014). For example, Stroop effects are resilient to practice but not immune, and can be significantly reduced by extensive practice in participants of almost every age (e.g., Dulaney & Rogers, 1994; Protopapas et al., 2014). Interestingly, it has been argued that the mechanism underlying changes in Stroop effects due to extensive practice is related to developing a new semi-automatic response of color detection, which can compete with the previously established automatic response of word reading. Similarly, it has been shown that extensive training can enhance performance in updating tasks but will not actually increase WM capacity (Diamond & Ling, 2016). Instead, a well-learned response empowers participants to utilize their cognitive control processes in a more efficient manner. To summarize, it has not only been shown that practice can enhance performance in inhibition and updating tasks but also that the mechanisms underlying these enhancements are the same as those mechanisms that are proposed by SATH for explaining the effects of task-relevant posthypnotic suggestions (Zahedi, Sturmer, et al., 2020).

Two aspects of the effects of hypnotic and posthypnotic suggestions need further consideration. First, posthypnotic suggestions can be turned on and off, by presenting a cue that had been mentioned in the suggestions (a process called anchoring) (e.g, Iani et al., 2006; Raz et al., 2003; Zahedi, Sturmer, et al., 2020). If learning a new trigger-response contingency is the mechanism underlying performance enhancements, should not these improvements be resilient, that is, be present even after posthypnotic suggestions have been deactivated? It has been repeatedly shown that learning can be context-dependent, especially if learned responses are not extensively practiced (overlearned). For instance, Abrahamse and Verwey (2008) have shown that changing the context causes participants to inhibit learned responses. In addition, Ruitenberg, De Kleine, Van der Lubbe, Verwey, and Abrahamse (2012) showed that changing contextual cues can be detrimental to learned responses, especially if the duration of practice is limited. The same may be true for the effects of posthypnotic suggestions. Especially if one considers that posthypnotic suggestions do not cause an automatic-response to be formed (Tobis & Kihlstrom, 2010), contextual dependencies can explain why the effects of posthypnotic suggestions vanish when they are deactivated.

Second, what are the benefits of hypnotic and posthypnotic suggestions if their effects can be understood in terms of practice? One should notice that practice-related enhancements in cognitive performance are often achieved through very extensive training regimes and confined to the trained cognitive skill (Diamond & Ling, 2016; Melby-Lervag, Redick, & Hulme, 2016). This is in contrast to suggestions, which can affect performance after a relatively short mental practice (Zahedi, Sturmer, et al., 2020) and can target cognitive functions rather than specific tasks (Lindelov et al., 2017). Therefore, as discussed in several studies, suggestions can be used to improve the efficacy and efficiency of cognitive training in both normal participants (Zahedi, Sturmer, et al., 2020) and brain-damaged patients (Lindelov et al., 2017).

Do observations corroborate the postulations of SATH about task-relevant suggestions? If the effects of hypnotic and posthypnotic suggestions are related to mental practice, performance enhancements in updating and inhibition tasks should be related to enhanced utilization of proactive control and decreased utilization of reactive control. Proactive control is a form of control, recruited in advance of a situation, where executive control might be necessary, without consideration of its actual necessity. In contrast, reactive control is employed only when the need for cognitive control, such as conflict resolution, has been detected (Braver, 2012). Consequently, during task completion under the influence of suggestions (1) frontal theta and beta activity, possibly indicating increased utilization of executive functions (Reinhart & Nguyen, 2019), should be increased, as observed by Zahedi et al. (2017) (Fig. 5A). (2) P3 amplitude, highlighting incorporation of top-down processes and attentional resources (Fonken, Kam, & Knight, 2020; Polich, 2007) should be increased, as has been repeatedly reported (e.g., Zahedi et al., 2019; Zahedi, Luczak, et al., 2020; Zahedi, Sturmer, et al., 2020) (Fig. 5B). And finally, (3) task load effects should decrease in both inhibition and updating tasks. For instance, in inhibition tasks, conflict resolution should improve, resulting in decreased brain activity in regions related to conflict detection, such as the ACC, which has been observed, for example, by e.g., Raz et al. (2005) (Fig 5C). Furthermore, under the influence of suggestions, brain activation related to habitual, prepotent but task-irrelevant responses should decrease, such as semantic activation caused by automatic word reading in the Stroop and similar tasks, which has been revealed by (I) decreased N400 amplitudes (Zahedi et al., 2019) and (II) decreased activity in brain regions related to semantic activation, such as fusiform gyrus, superior and middle temporal gyri, pre- and postcentral gyri, and supplementary motor area (Ulrich, Kiefer, Bongartz, Gron, & Hoenig, 2015). Also in updating tasks, task-load on working memory buffers should decrease as the result of enhancements caused by suggestions, as observed by Zahedi, Sturmer, et al. (2020).

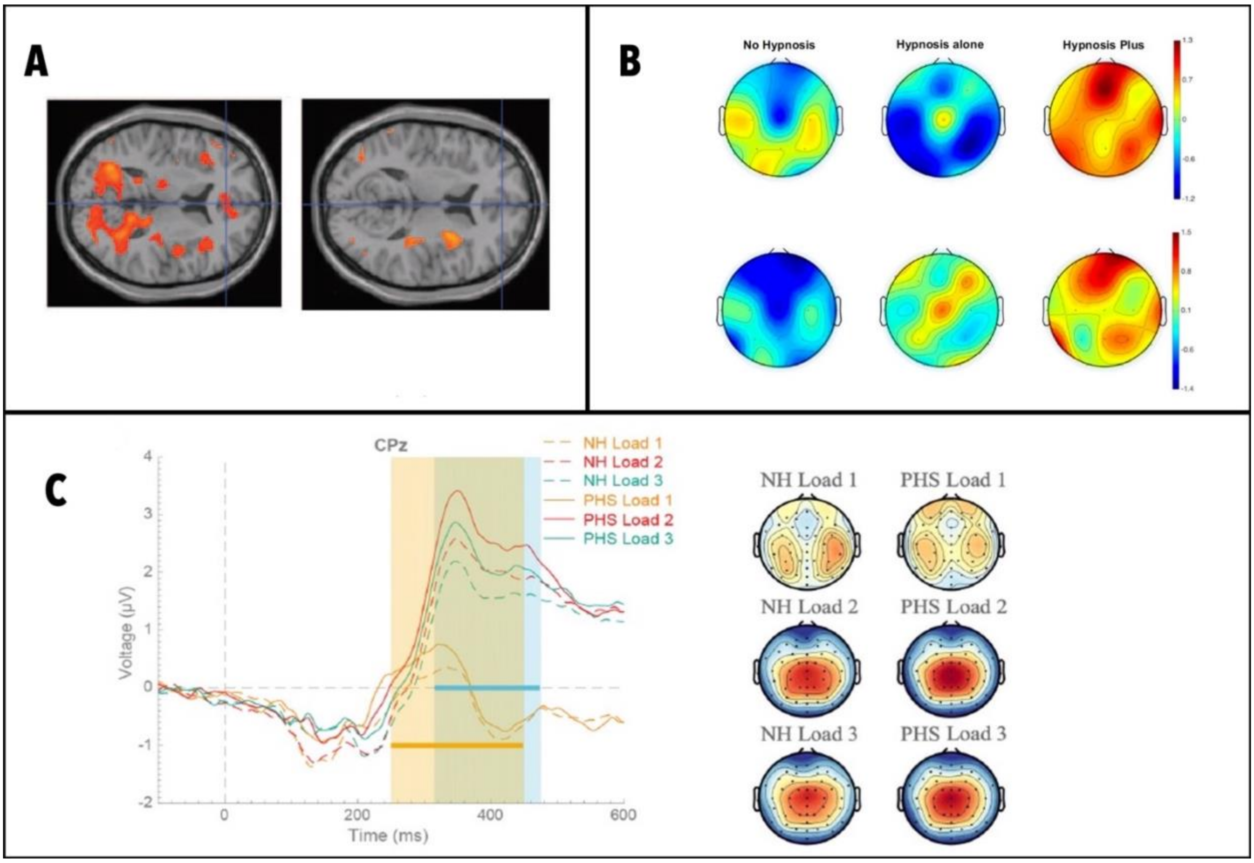


Figure 5. A) Activation of the ACC (marked by the blue crosshair) in high-hypnotizables during the completion of the Stroop task (left) in no-hypnosis condition and (right) under effects of posthypnotic suggestions (adapted with permission from Raz et al., 2005). B) (top) Theta and (bottom) beta activation during the completion of the Stroop task (adapted with permission from Zahedi et al., 2017). C) P3 amplitude during the completion of the tone-tracking task (measuring updating in working memory) (adapted with permission from Zahedi, Sturmer, et al., 2020).

As reviewed in section ***1.2. Objective Changes in Overt Behavior, Perception, and Cognition***, neutral hypnosis has no reliable effect on performance in cognitive tasks. According to

SATH, it is conceivable that only task-relevant suggestions, which can provide a ground for mental practice, may affect performance, and task-irrelevant suggestions, such as relaxation-inducing ones, presented during neutral hypnosis, will not affect performance in any systematic way. This conclusion aligns with published findings (e.g., Egner et al., 2005; Zahedi et al., 2017).

Considering alterations in the subjective SoA under the influence of hypnotic and posthypnotic suggestions targeting performance in cognitive tasks, it seems that developing a subjective sense of conviction, that is, the feeling that suggestions caused better performance, is more relevant rather than the experience of involuntariness, that is, conducting an action without attributing it to direct exertion of volitional effort. In other words, under the influence of suggestions, on one hand, participants may perform a cognitive task with less reactive cognitive control, and consequently less expenditure of effort, as they already had practiced the strategy and can implement it proactively and more efficiently. On the other hand, since participation in a cognitive task needs goal-directed effort, even if one is already well-equipped with appropriate responses, participants cannot sense involuntariness. This situation is similar to suggestion-induced changes in perception and can be contrasted with motor suggestions.

3.3.2. Effects of Suggestions on Memory

The last form of cognitive suggestions that needs to be discussed is related to memory and amnesia. As discussed in section ***1.2. Objective Changes in Overt Behavior, Perception, and Cognition***, there is no reliable evidence that suggestions can enhance memory performance. Negative effects of posthypnotic suggestions on memory are related to explicit memory and not implicit memory (Kihlstrom, 2014). Therefore, it seems that the negative effects of posthypnotic suggestions on memory resemble the production of false memories, which can be easily explained by cognitive-simulation. In fuzzy trace theory, Brainerd and Reyna (2016) hold that for every memory two separate sets of information are stored, namely, verbatim and gist traces. Verbatim traces contain precise information of the event, for instance, the exact words heard, or objects seen, and therefore, only one set of verbatim traces is stored for each event. In contrast, gist traces are related to the meaning of the event for the person, such as its emotional meaning, and consequently, several gist traces may be stored for a given event. Even though both gist and verbatim traces are stored in parallel, verbatim traces are more prone to become inaccessible. During remembering, both verbatim and gist traces can cause vivid remembering experiences. If we consider amnesia suggestions, it is evident that such suggestions are creating a new gist trace. For instance, participants are asked to imagine that a specific incident did not take place, or after showing them some words they are asked to imagine not to have seen any words. It is obvious that these suggestions are not targeting verbatim traces but creating a new gist trace. The new gist can lead to the formation of false memories (e.g., they had not seen words during hypnosis). But as verbatim traces are not affected, memory performance in implicit memory tasks, which is dependent on the precise information of events, must be intact. This suggestion is in line with observation in the literature (for review please see Kihlstrom, 2014).

3.3.3. Comparison with Other Theories

The only other theory that tries to explain the enhancing effects of suggestions on performance in cognitive tasks is the decoupling account, presented by Egner et al. (2005) (reviewed in section ***2.2.3. Decoupling Theory***). This account assumes that performance enhancements are caused by the disconnection of cognitive monitoring from cognitive control processes. In contrast, SATH assumes that top-down processes, and especially mental practice, may cause participants to learn new trigger-response contingencies, which helps them to perform more efficiently and successfully in cognitive tasks. This proposition has the advantage that it can also explain enhancements in tasks that can be only improved by top-down cognitive processes, such as updating tasks, which the decoupling account cannot explain.

3.4. Hypnotizability and its Determinants

Throughout the presentation of SATH, we did not discuss the important question of why not all participants respond to suggestions. SATH embraces the discussion of Kirsch (1997) and, hence, it distinguishes between general *suggestibility*, that is, the capability of a person to respond to suggestions regardless of hypnosis, and *hypnotizability*, that is, the increase in suggestibility due to the reception of hypnotic induction.

The top-down mechanisms discussed above are related to general suggestibility and not to hypnotizability. Considering SATH's proposition that there are several top-down processes involved in responding to suggestions, no single cognitive capability, such as the capability to fantasize, suppress irrelevant information, inhibit prepotent responses, or the ability to form new trigger-response contingencies, will suffice to respond to all kinds of suggestions. Even when considering a single hypnotic or posthypnotic suggestion, participants might use different mechanisms to different extents to comply with it. As an example, let's consider the hand levitation suggestion, discussed in section ***3.2. Motor Suggestion***. A participant, who is well capable to vividly imagine suggested stimuli (using cognitive-simulation) but less capable to maintain a focus on sensory input (causing sensory-adaptation), may rely more strongly on imagination while responding to the levitation suggestion, in order to render input from mental imagery more precise than predictions. Conversely, a person with the opposite distribution of capabilities, ceteris paribus, may rely more on sensory-adaptation, in order to decrease the precision of somatosensory input. However, one should notice that even though there is interpersonal variability in these cognitive capabilities, they are correlated to some extent. For instance, recent neuroimaging studies have shown that cognitive control, imagination, and openness are correlated, and their underlying neural systems overlap (e.g., Beaty et al., 2018).

Together, three predictions can be made about hypnotizability determinants and sub-groups of hypnotic-suggestibles by considering SATH. (1) The correlation between any single cognitive capability and general suggestibility should be moderate at best, and the results of different studies may be conflicting, especially if sample sizes are small. This is aligned with existing reports, for instance, about the correlation between general hypnotic-suggestibility (as measured by standardized scales such as HGSHS) and cognitive capabilities. Several well-conducted recent studies, using relatively small sample sizes ($36 \leq N \leq 40$), showed that in no-hypnosis conditions, high-hypnotic-suggestibles were better in cognitive tasks than low-hypnotic-suggestibles, inferred from psychometric measures and neural correlates (Kirenskaya et al., 2019; Srzich et al., 2019). Also, Cojan et al. (2015) showed that during a flanker task, high-hypnotic-suggestibles were more accurate but slower and low-hypnotizables were faster but less accurate. In addition, high-hypnotic-suggestibles showed greater activity in DLPFC but less activity in the ACC and parietal cortices. Hence, high-hypnotic-suggestibles appear to be better able to resolve conflicts whereas low-hypnotic-suggestibles may be better in detecting them. However, the sample of Cojan et al. (2015) was relatively small ($N = 32$) for investigating individual differences, limiting the interpretability of their results. In contrast to the reports above about the superiority of high-hypnotic-suggestibles, investigating several updating (working memory) tasks in a relatively small sample ($N = 36$), Khodaverdi-Khani and Laurence (2016) showed that digit span performance in high-hypnotic-suggestibles is inferior to low-hypnotizables. However, in their second sample ($N = 20$), there was no significant difference in an N-back task, rendering their findings inconclusive with regard to working memory performance. Interestingly, when the sample size increases, these correlations seem to disappear. In a sample of ($N = 180$), Dienes et al. (2009) found no significant correlation between inhibition and dissociation (closely related to sensory-adaptation) with hypnotizability.

(2) More importantly, SATH predicts that there are different groups of high-suggestibles, who use different capabilities in responding to suggestions. Intriguingly, the results of Terhune et al. (2011) confirm that there are at least two sub-groups of high-suggestibles, one relying more heavily on dissociation (closely related to sensory-adaptation) and the other on imaginations (closely related to cognitive-simulation).

(3) SATH predicts that there are several categories of suggestions, each relying more specifically on one of the proposed top-down cognitive processes, that is, cognitive-simulation, sensory-adaptation, and problem-solving and mental practice. Several studies (e.g., McConkey et al., 1980; Woody et al., 2005) have already shown that standardized scales of hypnotic suggestibility contain at least three clusters of suggestions, namely, ideomotor, challenge, and cognitive suggestions. As discussed in section ***3.2. Motor Suggestion***, ideomotor suggestions can be exerted by using only cognitive-simulation, whereas challenge suggestions require sensory-adaption in addition. Finally, cognitive suggestions in these standardized scales are non-elaborated suggestions, which require finding an appropriate strategy for responding to these suggestions, and therefore, they must rely on problem-solving, as well, for finding an appropriate strategy. To summarize, SATH explains why there are multiple suggestibilities (McConkey et al., 1980; Woody et al., 2005) and heterogeneity within high-hypnotic-suggestibles (Terhune et al., 2011).

But what about the relationship between suggestibility and psychosocial factors? SATH assumes that similar to the cognitive capabilities, psychosocial factors affect suggestibility. However, psychosocial factors are also of unique importance for determining hypnotizability, that is, the increase in suggestibility due to hypnotic induction. In line with this claim, it has been shown that when measuring hypnotic suggestibility – the combined effect of suggestibility and hypnotizability – psychosocial factors such as willingness to be hypnotized and openness of participants (Green & Lynn, 2011; Lynn, Laurence, et al., 2015), expectations about hypnosis (Kirsch & Lynn, 1997), rapport with the hypnotist (Lynn et al., 2019), and motivation to respond to suggestions (Jones & Spanos, 1982) are relevant. Even considering suggestibility, it should be noted that cognitive-simulation and sensory-adaptation are not complicated and special cognitive processes. For instance, top-down downregulation of sensory input can be observed also in non-human species (e.g., Manita et al., 2015; Saalmann & Kastner, 2009). In other words, regardless of baseline cognitive capabilities, to some extent, all participants can exert top-down control over perception. For example, in two previous studies with healthy participants, all of them showed top-down downregulation of neural activity, regardless of their performance in other tasks (Fazeli et al., 2014; Lopresti-Goodman et al., 2013). Therefore, even though baseline cognitive capabilities can be essential to predict participants' responses to suggestions, psychosocial factors contribute as well. In other words, even though top-down processes are fundamental in responding to suggestions, for responding to suggestions participants should nevertheless be willing and open, have a good rapport with the person presenting the suggestions, and so forth.

The last issue to be addressed is whether hypnosis causes an altered state of consciousness and whether hypnotizability is related to the capability of experiencing this special state. This "state of consciousness", however, is not defined clearly (Lynn, Green, et al., 2015; Lynn et al., 2019). In the hypnosis literature, states like being absorbed in reading a book or watching TV to the extent that one becomes dissociated from the environment, are used to describe "hypnotic-like" states of consciousness (Elkins et al., 2015; Shor & Orne, 1962). From these examples, two possible conclusions can be drawn. Either, states of consciousness are separate entities, similar to the energy state of an electron, which can only be changed discretely (the quantum definition). Alternatively, there is an infinite number of states of consciousness that cannot be distinguished from each other, like the position of an electron in an electron cloud (the cloud definition). Nonetheless, in both cases, it may be counterproductive to define hypnosis based on states of consciousness. As for using the quantum definition, there is no empirical evidence - to this day - showing states of consciousness can be distinguished (Koch & Hepp, 2006). And if one takes the second definition for granted, then hypnosis cannot be a state, but a group of states, which are delineated from other states arbitrarily and called hypnosis. Consequently, any change in the state of consciousness as a result of hypnosis might be considered as a byproduct of the cognitive mechanisms employed in hypnosis and hypnotic suggestions, rather than as a defining feature of hypnosis.

3.4.1. Comparison with Other Theories

Concerning hypnotizability and its determinants, SATH should be distinguished from the unified cognitive theory (reviewed in section ***2.3. Unified Cognitive Model***) and cold-control theory (reviewed in section ***2.5. Cold Control Theory***). The unified cognitive model assumes two mutually-exclusive styles of responding to hypnosis, one related to responding to suggestions in or out of hypnosis (constructive style) and one restricted to hypnotic conditions (concentrative style). In contrast, SATH proposes that there are several basic mechanisms underlying the effects of suggestions, all of which are necessary for responding to different suggestions. The advantage of SATH is that it can consistently explain both multiple hypnotizability and multiple groups of high-hypnotizables, which the unified cognitive theory cannot.

Further, in order to explain multiple hypnotizability, the cold-control theory assumes that for responding to some suggestions more severe blocking of higher-order thoughts (i.e., blocking third and second-order thoughts rather than second-order thoughts only), is required. In contrast, SATH does not attribute all variance in responding to hypnotic suggestions to the difficulty of items, but assumes that, besides psychosocial variables, multiple cognitive capabilities are involved in responding to suggestions. As reviewed above, the proposition of SATH appears to be more aligned with empirical evidence.

3.4. Towards a New Definition of Hypnosis

Even though APA division 30 has recently offered a new definition of hypnosis (Elkins et al., 2015), many researchers had complained about the evident inclination of this definition towards the state approach (Lynn, Green, et al., 2015; Lynn et al., 2019). Considering the discussion about the state approach in section ***3.4. Hypnotizability and its Determinants***, we also think that defining a phenomenon based on one of its possible byproducts is not satisfactory. One of the reasons that were mentioned for substituting the previous procedure-oriented definition of hypnosis (Green, Barabasz, Barrett, & Montgomery, 2005) with this new version is that the previous version was long and vague regarding the underlying mechanisms of the effects of suggestions (Elkins et al., 2015). Therefore, here we presented a very short, concrete, and procedure-oriented definition of hypnosis based on SATH.

SATH defines hypnosis as a situation, in which a cooperative and willing participant will receive and respond to certain suggestions provided by another person, designated the hypnotist. Three top-down processes are employed to different degrees and based on participant's capabilities in order to respond to different suggestions. (a) Cognitive-simulation results in imagination and the mental perception of the suggested stimuli. (b) Sensory-adaption causes top-down downregulation of sensory input, especially in case that sensory input is incongruent with mentally perceived stimuli. (c) Mental practice enables the participant to learn new trigger-response contingencies. Noteworthy, these mechanisms can also occur without the hypnosis induction but may be enhanced in participants who have positive expectations about the hypnotic procedure.

3.5. Conclusions

In conclusion, we proposed the simulation-adaptation theory of hypnosis (SATH) and evaluated it based on the same criteria that we applied to other theories. SATH (I) can explain changes in objectively measured perceptions, that is, positive and negative hallucinations, and in the subjective sense of conviction accompanying these changes by proposing cognitive-simulation and sensory-adaption as underlying mechanisms. (II) Effects of motor suggestions and the sensation of involuntariness, that is, alterations in the subjective SoA during hypnotic-suggestion-induced overt responses, are explained by combining the above-mentioned mechanisms in conjunction with predictive coding. (III) Performance enhancements in executive function tasks are accounted for by proposing mental practice as the fundamental mechanism underlying these effects. (IV) SATH relates posthypnotic amnesia to the formation of new gist traces, which lead to increased false-memory generation. Finally (V) based on SATH, the existence of different groups of suggestions and different sub-groups of high-suggestibles are related to more salient reliance of different forms of suggestions on different basic mechanisms, and the possibility of responding to the same suggestion by using different combinations of basic capabilities. Even though theoretically complex, SATH can explain a broader range of hypnotic phenomena than any other existing theory of hypnosis and makes many testable (falsifiable) predictions, including hypotheses about the neural correlates of these phenomena. Hence, the proposed theory may advance our understanding of hypnosis, hypnotic suggestions, and their consequences.

Acknowledgment

This work was supported by a scholarship to A.Z. by the Deutscher Akademischer Austauschdienst (DAAD).

References

Abrahamse, E. L., & Verwey, W. B. (2008). Context dependent learning in the serial RT task. *Psychological Research, 72*(4), 397-404. doi:10.1007/s00426-007-0123-5

Adams, R. A., Shipp, S., & Friston, K. J. (2013). Predictions not commands: active inference in the motor system. *Brain Struct Funct, 218*(3), 611-643. doi:10.1007/s00429-012-0475-5

Alladin, A., & Alibhai, A. (2007). Cognitive hypnotherapy for depression: an empirical investigation. *International Journal of Clinical and Experimental Hypnosis, 55*(2), 147-166. doi:10.1080/00207140601177897

Augustinova, M., & Ferrand, L. (2012). Suggestion does not de-automatize word reading: evidence from the semantically based Stroop task. *Psychonmic Bulletin and Review, 19*(3), 521-527. doi:10.3758/s13423-012-0217-y

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience, 4*(10), 829-839. doi:10.1038/nrn1201

Barnier, A., & Mitchell, C. (2005). *Looking for the fundamental effects of hypnosis.* Paper presented at the Invited address at the 35th annual congress of the Australian society of hypnosis (scientific program), Sydney, Australia.

Barnier, A. J., Bryant, R. A., & Briscoe, S. (2001). Posthypnotic amnesia for material learned before or during hypnosis: explicit and implicit memory effects. *International Journal of Clinical and Experimental Hypnosis, 49*(4), 286-304. doi:10.1080/00207140108410079

Barnier, A. J., Dienes, Z., & Mitchell, C. J. (2012).

Beaty, R. E., Chen, Q., Christensen, A. P., Qiu, J., Silvia, P. J., & Schacter, D. L. (2018). Brain networks of the imaginative mind: Dynamic functional connectivity of default and cognitive control networks relates to openness to experience. *Human Brain Mapping, 39*(2), 811-821. doi:10.1002/hbm.23884

Blakemore, S. J., Oakley, D. A., & Frith, C. D. (2003). Delusions of alien control in the normal brain. *Neuropsychologia, 41*(8), 1058-1067. doi:10.1016/s0028-3932(02)00313-5

Bongartz, W. (1985). German norms for the Harvard Group Scale of Hypnotic Susceptibility, Form A. *International Journal of Clinical and Experimental Hypnosis, 33*(2), 131-139. doi:10.1080/00207148508406643

Botvinick, M. M. (2007). Conflict monitoring and decision making: reconciling two perspectives on anterior cingulate function. *Cognitive, Affective & Behavioral Neuroscience, 7*(4), 356-366. doi:10.3758/cabn.7.4.356

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*(3), 624-652. doi:10.1037/0033-295X.108.3.624

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. *Trends in Cognitive Sciences, 8*(12), 539-546. doi:10.1016/j.tics.2004.10.003

Bowers, P., Laurence, J. R., & Hart, D. (1988). The experience of hypnotic suggestions. *International Journal of Clinical and Experimental Hypnosis, 36*(4), 336-349. doi:10.1080/00207148808410523

Braffman, W., & Kirsch, I. (1999). Imaginative suggestibility and hypnotizability: an empirical analysis. *Journal of Personality and Social Psychology, 77*(3), 578-587. doi:10.1037//0022-3514.77.3.578

Brainerd, C. J., & Reyna, V. F. (2016). Fuzzy-Trace Theory and False Memory. *Current Directions in Psychological Science, 11*(5), 164-169. doi:10.1111/1467-8721.00192

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends in Cognitive Sciences, 16*(2), 106-113. doi:10.1016/j.tics.2011.12.010

Brown, H., Adams, R. A., Parees, I., Edwards, M., & Friston, K. (2013). Active inference, sensory attenuation and illusions. *Cognitive Processing, 14*(4), 411-427. doi:10.1007/s10339-013-0571-3

Brown, R. J., Antonova, E., Langley, A., & Oakley, D. A. (2001). The effects of absorption and reduced critical thought on suggestibility in an hypnotic context. *Contemporary Hypnosis, 18*(2), 62-72. doi:10.1002/ch.220

Brown, R. J., & Oakley, D. A. (2004). An integrative cognitive theory of hypnosis and high hypnotizability. *The highly hypnotizable person: Theoretical, experimental and clinical issues*, 152-186.

Bryant, R. A., Barnier, A. J., Mallard, D., & Tibbits, R. (1999). Posthypnotic amnesia for material learned before hypnosis. *International Journal of Clinical and Experimental Hypnosis, 47*(1), 46-64. doi:10.1080/00207149908410022

Carter, C. S., Macdonald, A. M., Botvinick, M., Ross, L. L., Stenger, V. A., Noll, D., & Cohen, J. D. (2000). Parsing executive processes: strategic vs. evaluative functions of the anterior cingulate cortex. *Proceedings of the National Academy of Sciences of the United States of America, 97*(4), 1944-1948. doi:10.1073/pnas.97.4.1944

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences, 36*(3), 181-204. doi:10.1017/S0140525X12000477

Cojan, Y., Archimi, A., Cheseaux, N., Waber, L., & Vuilleumier, P. (2013). Time-course of motor inhibition during hypnotic paralysis: EEG topographical and source analysis. *Cortex, 49*(2), 423-436. doi:10.1016/j.cortex.2012.09.013

Cojan, Y., Piguet, C., & Vuilleumier, P. (2015). What makes your brain suggestible? Hypnotizability is associated with differential brain activity during attention outside hypnosis. *Neuroimage, 117*, 367-374. doi:10.1016/j.neuroimage.2015.05.076

Cojan, Y., Waber, L., Schwartz, S., Rossier, L., Forster, A., & Vuilleumier, P. (2009). The brain under self-control: modulation of inhibitory and monitoring cortical networks during hypnotic paralysis. *Neuron, 62*(6), 862-875. doi:10.1016/j.neuron.2009.05.021

Cooper, R., & Shallice, T. (2000). Contention scheduling and the control of routine activities. *Cognitive Neuropsychology, 17*(4), 297-338. doi:10.1080/026432900380427

Custers, R., & Aarts, H. (2010). The unconscious will: how the pursuit of goals operates outside of conscious awareness. *Science, 329*(5987), 47-50. doi:10.1126/science.1188595

David, D., Brown, R., Pojoga, C., & David, A. (2000). The impact of posthypnotic amnesia and directed forgetting on implicit and explicit memory: new insights from a modified process dissociation procedure. *International Journal of Clinical and Experimental Hypnosis, 48*(3), 267-289. doi:10.1080/00207140008415246

Deeley, Q., Oakley, D. A., Walsh, E., Bell, V., Mehta, M. A., & Halligan, P. W. (2014). Modelling psychiatric and cultural possession phenomena with suggestion and fMRI. *Cortex, 53*, 107-119. doi:10.1016/j.cortex.2014.01.004

Deeley, Q., Walsh, E., Oakley, D. A., Bell, V., Koppel, C., Mehta, M. A., & Halligan, P. W. (2013). Using hypnotic suggestion to model loss of control and awareness of movements: an exploratory FMRI study. *PloS One, 8*(10), e78324. doi:10.1371/journal.pone.0078324

DePrince, A. P., & Freyd, J. J. (1999). Dissociative Tendencies, Attention, and Memory. *Psychological Science, 10*(5), 449-452. doi:10.1111/1467-9280.00185

Derbyshire, S. W., Whalley, M. G., Stenger, V. A., & Oakley, D. A. (2004). Cerebral activation during hypnotically induced and imagined pain. *Neuroimage, 23*(1), 392-401. doi:10.1016/j.neuroimage.2004.04.033

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135-168. doi:10.1146/annurev-psych-113011-143750

Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental Cognitive Neuroscience, 18*, 34-48. doi:10.1016/j.dcn.2015.11.005

Dienes, Z., Beran, M., Brandl, J. L., Perner, J., & Proust, J. (2012). Is hypnotic responding the strategic relinquishment of metacognition. *Foundations of metacognition*, 267-277.

Dienes, Z., Brown, E., Hutton, S., Kirsch, I., Mazzoni, G., & Wright, D. B. (2009). Hypnotic suggestibility, cognitive inhibition, and dissociation. *Consciousness and Cognition, 18*(4), 837-847. doi:10.1016/j.concog.2009.07.009

Dienes, Z., & Hutton, S. (2013). Understanding hypnosis metacognitively: rTMS applied to left DLPFC increases hypnotic suggestibility. *Cortex, 49*(2), 386-392. doi:10.1016/j.cortex.2012.07.009

Dienes, Z., & Perner, J. (2007). Executive control without conscious awareness: The cold control theory of hypnosis. *Hypnosis and conscious states: The cognitive neuroscience perspective*, 293-314.

Dulaney, C. L., & Rogers, W. A. (1994). Mechanisms underlying reduction in Stroop interference with practice for young and old adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20*(2), 470-484. doi:10.1037//0278-7393.20.2.470

Egner, T., Jamieson, G., & Gruzelier, J. (2005). Hypnosis decouples cognitive control from conflict monitoring processes of the frontal lobe. *Neuroimage, 27*(4), 969-978. doi:10.1016/j.neuroimage.2005.05.002

Egner, T., & Raz, A. (2007). Cognitive control processes and hypnosis. *Hypnosis and conscious states: The cognitive neuroscience perspective*, 29-50.

Elkins, G. R., Barabasz, A. F., Council, J. R., & Spiegel, D. (2015). Advancing research and practice: The revised APA Division 30 definition of hypnosis. *American Journal of Clinical Hypnosis, 57*(4), 378-385. doi:10.1080/00029157.2015.1011465

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance, 27*(1), 229-240. doi:10.1037/0096-1523.27.1.229

Farah, M. J. (1988). Is visual imagery really visual? Overlooked evidence from neuropsychology. *Psychological Review, 95*(3), 307-317. doi:10.1037/0033-295x.95.3.307

Fazeli, A., Haji-Abdolvahab, M., Shojaosadati, S. A., Schellekens, H., Khalifeh, K., Moosavi-Movahedi, A. A., & Fazeli, M. R. (2014). Effect of arginine on pre-nucleus stage of interferon beta-1b aggregation. *AAPS PharmSciTech, 15*(6), 1619-1629. doi:10.1208/s12249-014-0192-x

Fonken, Y. M., Kam, J. W. Y., & Knight, R. T. (2020). A differential role for human hippocampus in novelty and contextual processing: Implications for P300. *Psychophysiology, 57*(7), e13400. doi:10.1111/psyp.13400

Frank, C., Land, W. M., & Schack, T. (2015). Perceptual-cognitive changes during motor learning: the influence of mental and physical practice on mental representation, gaze behavior, and performance of a complex action. *Frontiers in Psychology, 6*, 1981. doi:10.3389/fpsyg.2015.01981

Frank, T. D. (2016). Perception adapts via top-down regulation to task repetition: A Lotka-Volterra-Haken modeling analysis of experimental data. *Journal of Integrative Neuroscience, 15*(1), 67-79. doi:10.1142/S0219635216500059

Friston, K. (2010). The free-energy principle: a unified brain theory? *Nature Reviews: Neuroscience, 11*(2), 127-138. doi:10.1038/nrn2787

Frith, C. D., Blakemore, S. J., & Wolpert, D. M. (2000). Abnormalities in the awareness and control of action. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 355*(1404), 1771-1788. doi:10.1098/rstb.2000.0734

Galea, V., Woody, E. Z., Szechtman, H., & Pierrynowski, M. R. (2010). Motion in response to the hypnotic suggestion of arm rigidity: a window on underlying mechanisms. *International Journal of Clinical and Experimental Hypnosis, 58*(3), 251-268. doi:10.1080/00207141003760561

Gandhi, B., & Oakley, D. A. (2005). Does 'hypnosis' by any other name smell as sweet? The efficacy of 'hypnotic' inductions depends on the label 'hypnosis'. *Consciousness and Cognition, 14*(2), 304-315. doi:10.1016/j.concog.2004.12.004

Ganis, G., & Schendan, H. E. (2008). Visual mental imagery and perception produce opposite adaptation effects on early brain potentials. *Neuroimage, 42*(4), 1714-1727. doi:10.1016/j.neuroimage.2008.07.004

Gilman, J. M., Ramchandani, V. A., Davis, M. B., Bjork, J. M., & Hommer, D. W. (2008). Why we like to drink: a functional magnetic resonance imaging study of the rewarding and anxiolytic effects of alcohol. *Journal of Neuroscience, 28*(18), 4583-4591. doi:10.1523/JNEUROSCI.0086-08.2008

Gobel, E. W., Parrish, T. B., & Reber, P. J. (2011). Neural correlates of skill acquisition: decreased cortical activity during a serial interception sequence learning task. *Neuroimage, 58*(4), 1150-1157. doi:10.1016/j.neuroimage.2011.06.090

Gorassini, D. R., & Spanos, N. P. (1986). A social-cognitive skills approach to the successful modification of hypnotic susceptibility. *Journal of Personality and Social Psychology, 50*(5), 1004-1012. doi:10.1037//0022-3514.50.5.1004

Green, J. P., Barabasz, A. F., Barrett, D., & Montgomery, G. H. (2005). Forging ahead: the 2003 APA Division 30 definition of hypnosis. *International Journal of Clinical and Experimental Hypnosis, 53*(3), 259-264. doi:10.1080/00207140590961321

Green, J. P., & Lynn, S. J. (2011). Hypnotic responsiveness: expectancy, attitudes, fantasy proneness, absorption, and gender. *International Journal of Clinical and Experimental Hypnosis, 59*(1), 103-121. doi:10.1080/00207144.2011.522914

Hammond, D. C. (1990). *Handbook of hypnotic suggestions and metaphors*: WW Norton & Company.

Hammond, D. C. (1998). *Hypnotic induction and suggestion*. Chicago, IL: American Society of Clinical Hypnosis.

Hesslow, G. (2002). Conscious thought as simulation of behaviour and perception. *Trends in Cognitive Sciences, 6*(6), 242-247. doi:10.1016/s1364-6613(02)01913-7

Hilgard, E. R. (1973). A neodissociation interpretation of pain reduction in hypnosis. *Psychological Review, 80*(5), 396-411. doi:10.1037/h0020073

Hilgard, E. R. (1977). The problem of divided consciousness: a neodissociation interpretation. *Annals of the New York Academy of Sciences, 296*, 48-59. doi:10.1111/j.1749-6632.1977.tb38160.x

Hommel, B., Musseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): a framework for perception and action planning. *Behavioral and Brain Sciences, 24*(5), 849-878; discussion 878-937. doi:10.1017/s0140525x01000103

Iani, C., Ricci, F., Baroni, G., & Rubichi, S. (2009). Attention control and susceptibility to hypnosis. *Consciousness and Cognition, 18*(4), 856-863. doi:10.1016/j.concog.2009.07.002

Iani, C., Ricci, F., Gherri, E., & Rubichi, S. (2006). Hypnotic suggestion modulates cognitive conflict: the case of the flanker compatibility effect. *Psychological Science, 17*(8), 721-727. doi:10.1111/j.1467-9280.2006.01772.x

Jahn, A., Nee, D. E., Alexander, W. H., & Brown, J. W. (2014). Distinct regions of anterior cingulate cortex signal prediction and outcome evaluation. *Neuroimage, 95*, 80-89. doi:10.1016/j.neuroimage.2014.03.050

Jamieson, G. A. (2016). A unified theory of hypnosis and meditation states: The interoceptive predictive coding approach.

Jamieson, G. A., & Sheehan, P. W. (2004). An empirical test of Woody and Bowers's dissociated-control theory of hypnosis. *International Journal of Clinical and Experimental Hypnosis, 52*(3), 232-249. doi:10.1080/0020714049052349

Jamieson, G. A., & Woody, E. (2007). Dissociated control as a paradigm for cognitive neuroscience research and theorizing in hypnosis. *Hypnosis and conscious states: The cognitive neuroscience perspective*, 111-129.

Jensen, M. P., Adachi, T., Tome-Pires, C., Lee, J., Osman, Z. J., & Miro, J. (2015). Mechanisms of hypnosis: toward the development of a biopsychosocial model. *International Journal of Clinical and Experimental Hypnosis, 63*(1), 34-75. doi:10.1080/00207144.2014.961875

Jensen, M. P., Jamieson, G. A., Lutz, A., Mazzoni, G., McGeown, W. J., Santarcangelo, E. L., . . . Terhune, D. B. (2017). New directions in hypnosis research: strategies for advancing the cognitive and clinical neuroscience of hypnosis. *Neurosci Conscious, 3*(1). doi:10.1093/nc/nix004

Jones, B., & Spanos, N. P. (1982). Suggestions for altered auditory sensitivity, the negative subject effect and hypnotic susceptibility: A signal detection analysis. *Journal of Personality and Social Psychology, 43*(3), 637-647. doi:10.1037/0022-3514.43.3.637

Jung, R. E., Flores, R. A., & Hunter, D. (2016). A New Measure of Imagination Ability: Anatomical Brain Imaging Correlates. *Frontiers in Psychology, 7*, 496. doi:10.3389/fpsyg.2016.00496

Kerns, J. G., Cohen, J. D., MacDonald, A. W., 3rd, Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303*(5660), 1023-1026. doi:10.1126/science.1089910

Khodaverdi-Khani, M., & Laurence, J.-R. (2016). Working memory and hypnotizability. *Psychology of Consciousness: Theory, Research, and Practice, 3*(1), 80-92. doi:10.1037/cns0000058

Kihlstrom, J. F. (1980). Posthypnotic amnesia for recently learned material: Interactions with “episodic” and “semantic” memory. *Cognitive Psychology, 12*(2), 227-251. doi:10.1016/0010-0285(80)90010-9

Kihlstrom, J. F. (1985). Hypnosis. *Annual Review of Psychology, 36*, 385-418. doi:10.1146/annurev.ps.36.020185.002125

Kihlstrom, J. F. (2008). The domain of hypnosis, revisited. *The Oxford handbook of hypnosis: Theory, research and practice*, 21-52.

Kihlstrom, J. F. (2014). Hypnosis and cognition. *Psychology of Consciousness: Theory, Research, and Practice, 1*(2), 139-152. doi:10.1037/cns0000014

Kihlstrom, J. F., Glisky, M. L., & Angiulo, M. J. (1994). Dissociative tendencies and dissociative disorders. *Journal of Abnormal Psychology, 103*(1), 117-124. doi:10.1037/0021-843x.103.1.117

Kirenskaya, A. V., Storozheva, Z. I., Solntseva, S. V., Novototsky-Vlasov, V. Y., & Gordeev, M. N. (2019). Auditory Evoked Potentials Evidence for Differences in Information Processing between High and Low Hypnotizable Subjects. *International Journal of Clinical and Experimental Hypnosis, 67*(1), 81-103. doi:10.1080/00207144.2019.1553764

Kirsch, I. (1996). Hypnotic enhancement of cognitive-behavioral weight loss treatments—Another meta-reanalysis. *Journal of Consulting and Clinical Psychology, 64*(3), 517-519. doi:10.1037/0022-006x.64.3.517

Kirsch, I. (1997). Suggestibility or hypnosis: what do our scales really measure? *International Journal of Clinical and Experimental Hypnosis, 45*(3), 212-225. doi:10.1080/00207149708416124

Kirsch, I. (1999). Hypnosis and placebos: response expectancy as a mediator of suggestion effects. *Anales de Psicología*.

Kirsch, I., & Lynn, S. J. (1997). Hypnotic involuntariness and the automaticity of everyday life. *American Journal of Clinical Hypnosis, 40*(1), 329-348. doi:10.1080/00029157.1997.10403402

Kirsch, I., & Lynn, S. J. (1998). Dissociation theories of hypnosis. *Psychological Bulletin, 123*(1), 100-115. doi:10.1037/0033-2909.123.1.100

Koch, C., & Hepp, K. (2006). Quantum mechanics in the brain. *Nature, 440*(7084), 611. doi:10.1038/440611a

Landry, M., Lifshitz, M., & Raz, A. (2017). Brain correlates of hypnosis: A systematic review and meta-analytic exploration. *Neuroscience and Biobehavioral Reviews, 81*(Pt A), 75-98. doi:10.1016/j.neubiorev.2017.02.020

Lau, H. C., & Passingham, R. E. (2007). Unconscious activation of the cognitive control system in the human prefrontal cortex. *Journal of Neuroscience, 27*(21), 5805-5811. doi:10.1523/JNEUROSCI.4335-06.2007

Lifshitz, M., Aubert Bonn, N., Fischer, A., Kashem, I. F., & Raz, A. (2013). Using suggestion to modulate automatic processes: from Stroop to McGurk and beyond. *Cortex, 49*(2), 463-473. doi:10.1016/j.cortex.2012.08.007

Lindelov, J. K., Overgaard, R., & Overgaard, M. (2017). Improving working memory performance in brain-injured patients using hypnotic suggestion. *Brain, 140*(4), 1100-1106. doi:10.1093/brain/awx001

Lopresti-Goodman, S. M., Turvey, M. T., & Frank, T. D. (2013). Negative hysteresis in the behavioral dynamics of the affordance "graspable". *Atten Percept Psychophys, 75*(5), 1075-1091. doi:10.3758/s13414-013-0437-x

Ludwig, V. U., Seitz, J., Schonfeldt-Lecuona, C., Hose, A., Abler, B., Hole, G., . . . Walter, H. (2015). The neural correlates of movement intentions: A pilot study comparing hypnotic and simulated paralysis. *Consciousness and Cognition, 35*, 158-170. doi:10.1016/j.concog.2015.05.010

Ludwig, V. U., Stelzel, C., Krutiak, H., Magrabi, A., Steimke, R., Paschke, L. M., . . . Walter, H. (2014). The suggestible brain: posthypnotic effects on value-based decision-making. *Social Cognitive and Affective Neuroscience, 9*(9), 1281-1288. doi:10.1093/scan/nst110

Lush, P., Botan, V., Scott, R. B., Seth, A. K., Ward, J., & Dienes, Z. (2020). Trait phenomenological control predicts experience of mirror synaesthesia and the rubber hand illusion. *Nat Commun, 11*(1), 4853. doi:10.1038/s41467-020-18591-6

Lynn, S. J., & Green, J. P. (2011). The sociocognitive and dissociation theories of hypnosis: toward a rapprochement. *International Journal of Clinical and Experimental Hypnosis, 59*(3), 277-293. doi:10.1080/00207144.2011.570652

Lynn, S. J., Green, J. P., Kirsch, I., Capafons, A., Lilienfeld, S. O., Laurence, J. R., & Montgomery, G. H. (2015). Grounding Hypnosis in Science: The "New" APA Division 30 Definition of Hypnosis as a Step Backward. *American Journal of Clinical Hypnosis, 57*(4), 390-401. doi:10.1080/00029157.2015.1011472

Lynn, S. J., Green, J. P., Polizzi, C. P., Ellenberg, S., Gautam, A., & Aksen, D. (2019). Hypnosis, hypnotic phenomena, and hypnotic responsiveness: Clinical and Research Foundations-A 40-Year Perspective. *International Journal of Clinical and Experimental Hypnosis, 67*(4), 475-511. doi:10.1080/00207144.2019.1649541

Lynn, S. J., Laurence, J. R., & Kirsch, I. (2015). Hypnosis, suggestion, and suggestibility: an integrative model. *American Journal of Clinical Hypnosis, 57*(3), 314-329. doi:10.1080/00029157.2014.976783

Lynn, S. J., Nash, M. R., Rhue, J. W., Frauman, D. C., & Sweeney, C. A. (1984). Nonvolition, expectancies, and hypnotic rapport. *Journal of Abnormal Psychology, 93*(3), 295-303. doi:10.1037/0021-843x.93.3.295

Lynn, S. J., Neufeld, V., & Matyi, C. L. (1987). Inductions versus suggestions: Effects of direct and indirect wording on hypnotic responding and experience. *Journal of Abnormal Psychology, 96*(1), 76-79. doi:10.1037/0021-843x.96.1.76

Lynn, S. J., Rhue, J. W., & Weekes, J. R. (1990). Hypnotic involuntariness: A social cognitive analysis. *Psychological Review, 97*(2), 169-184. doi:10.1037/0033-295x.97.2.169

Manita, S., Suzuki, T., Homma, C., Matsumoto, T., Odagawa, M., Yamada, K., . . . Murayama, M. (2015). A Top-Down Cortical Circuit for Accurate Sensory Perception. *Neuron, 86*(5), 1304-1316. doi:10.1016/j.neuron.2015.05.006

Martin, J. R., & Pacherie, E. (2019). Alterations of agency in hypnosis: A new predictive coding model. *Psychological Review, 126*(1), 133-152. doi:10.1037/rev0000134

Matthews, W. J., Bennett, H., Bean, W., & Gallagher, M. (1985). Indirect versus direct hypnotic suggestions--an initial investigation: a brief communication. *International Journal of Clinical and Experimental Hypnosis, 33*(3), 219-223. doi:10.1080/00207148508406650

Mazzoni, G., Rotriquenz, E., Carvalho, C., Vannucci, M., Roberts, K., & Kirsch, I. (2009). Suggested visual hallucinations in and out of hypnosis. *Consciousness and Cognition, 18*(2), 494-499. doi:10.1016/j.concog.2009.02.002

McConkey, K. M., Sheehan, P. W., & Law, H. G. (1980). Structural analysis of the Harvard Group Scale of Hypnotic Susceptibility, Form A. *International Journal of Clinical and Experimental Hypnosis, 28*(2), 164-175. doi:10.1080/00207148008409838

McGeown, W. J., Venneri, A., Kirsch, I., Nocetti, L., Roberts, K., Foan, L., & Mazzoni, G. (2012). Suggested visual hallucination without hypnosis enhances activity in visual areas of the brain. *Consciousness and Cognition, 21*(1), 100-116. doi:10.1016/j.concog.2011.10.015

Melby-Lervag, M., Redick, T. S., & Hulme, C. (2016). Working memory training does not improve performance on measures of intelligence or other measures of "ar transfer": evidence from a meta-analytic review. *Perspectives on Psychological Science, 11*(4), 512-534. doi:10.1177/1745691616635612

Melcher, T., Weidema, M., Eenshuistra, R. M., Hommel, B., & Gruber, O. (2008). The neural substrate of the ideomotor principle: an event-related fMRI analysis. *Neuroimage, 39*(3), 1274-1288. doi:10.1016/j.neuroimage.2007.09.049

Melcher, T., Winter, D., Hommel, B., Pfister, R., Dechent, P., & Gruber, O. (2013). The neural substrate of the ideomotor principle revisited: evidence for asymmetries in action-effect learning. *Neuroscience, 231*, 13-27. doi:10.1016/j.neuroscience.2012.11.035

Metcalfe, J., Van Snellenberg, J. X., DeRosse, P., Balsam, P., & Malhotra, A. K. (2012). Judgements of agency in schizophrenia: an impairment in autonoetic metacognition. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 367*(1594), 1391-1400. doi:10.1098/rstb.2012.0006

Miall, R. C., & Wolpert, D. M. (1996). Forward Models for Physiological Motor Control. *Neural Networks, 9*(8), 1265-1279. doi:10.1016/s0893-6080(96)00035-4

Miele, D. B., Wager, T. D., Mitchell, J. P., & Metcalfe, J. (2011). Dissociating neural correlates of action monitoring and metacognition of agency. *Journal of Cognitive Neuroscience, 23*(11), 3620-3636. doi:10.1162/jocn_a_00052

Milburn, M. C. (2010). Cognitive-Behavior Therapy and Change: Unconditional Self Acceptance and Hypnosis in CBT. *Journal of Rational-Emotive and Cognitive-Behavior Therapy, 29*(3), 177-191. doi:10.1007/s10942-010-0121-1

Milling, L. S., Gover, M. C., & Moriarty, C. L. (2018). The effectiveness of hypnosis as an intervention for obesity: A meta-analytic review. *Psychology of Consciousness: Theory, Research, and Practice, 5*(1), 29-45. doi:10.1037/cns0000139

Miyake, A., & Friedman, N. P. (2012). The Nature and Organization of Individual Differences in Executive Functions: Four General Conclusions. *Current Directions in Psychological Science, 21*(1), 8-14. doi:10.1177/0963721411429458

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cognitive Psychology, 41*(1), 49-100. doi:10.1006/cogp.1999.0734

Morewedge, C. K., Huh, Y. E., & Vosgerau, J. (2010). Thought for food: imagined consumption reduces actual consumption. *Science, 330*(6010), 1530-1533. doi:10.1126/science.1195701

Naccache, L., & Dehaene, S. (2001). Unconscious semantic priming extends to novel unseen stimuli. *Cognition, 80*(3), 215-229. doi:10.1016/s0010-0277(00)00139-6

Nemeth, D., Janacsek, K., Polner, B., & Kovacs, Z. A. (2013). Boosting human learning by hypnosis. *Cerebral Cortex, 23*(4), 801-805. doi:10.1093/cercor/bhs068

Niendam, T. A., Laird, A. R., Ray, K. L., Dean, Y. M., Glahn, D. C., & Carter, C. S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cognitive, Affective & Behavioral Neuroscience, 12*(2), 241-268. doi:10.3758/s13415-011-0083-5

Norman, D. A., & Shallice, T. (1986). Attention to Action. In *Consciousness and Self-Regulation* (pp. 1-18).

Oakman, J. M., & Woody, E. Z. (1996). A taxometric analysis of hypnotic susceptibility. *Journal of Personality and Social Psychology, 71*(5), 980-991. doi:10.1037/0022-3514.71.5.980

Palfi, B., Parris, B. A., McLatchie, N., Kekecs, Z., & Dienes, Z. (2020). Can unconscious intentions be more effective than conscious intentions? Test of the role of metacognition in hypnotic response. *Cortex*. doi:10.1016/j.cortex.2020.11.006

Parris, B. A. (2017). The role of frontal executive functions in hypnosis and hypnotic suggestibility. *Psychology of Consciousness: Theory, Research, and Practice, 4*(2), 211-229. doi:10.1037/cns0000106

Parris, B. A., & Dienes, Z. (2013). Hypnotic suggestibility predicts the magnitude of the imaginative word blindness suggestion effect in a non-hypnotic context. *Consciousness and Cognition, 22*(3), 868-874. doi:10.1016/j.concog.2013.05.009

Perri, R. L., Facco, E., Quinzi, F., Bianco, V., Berchicci, M., Rossani, F., & Di Russo, F. (2020). Cerebral mechanisms of hypnotic hypoesthesia. An ERP investigation on the expectancy stage of perception. *Psychophysiology*, e13657. doi:10.1111/psyp.13657

Perri, R. L., Rossani, F., & Di Russo, F. (2019). Neuroelectric evidences of top-down hypnotic modulation associated with somatosensory processing of sensory and limbic regions. *Neuroimage, 202*, 116104. doi:10.1016/j.neuroimage.2019.116104

Piccione, C., Hilgard, E. R., & Zimbardo, P. G. (1989). On the degree of stability of measured hypnotizability over a 25-year period. *Journal of Personality and Social Psychology, 56*(2), 289-295.

Piesbergen, C., & Peter, B. (2006). An investigation of the factor structure of the Harvard Group Scale of Hypnotic Susceptibility, Form A (HGSHS:A). *Contemporary Hypnosis, 23*(2), 59-71. doi:10.1002/ch.311

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology, 118*(10), 2128-2148. doi:10.1016/j.clinph.2007.04.019

Popper, K. R. (1971). CONJECTURAL KNOWLEDGE: MY SOLUTION OF THE PROBLEM OF INDUCTION. *Revue Internationale De Philosophie, 25(95/96 (1/2))*, 167-197.

Protopapas, A., Vlahou, E. L., Moirou, D., & Ziaka, L. (2014). Word reading practice reduces Stroop interference in children. *Acta Psychologica, 148*, 204-208. doi:10.1016/j.actpsy.2014.02.006

Pyka, M., Burgmer, M., Lenzen, T., Pioch, R., Dannlowski, U., Pfleiderer, B., . . . Konrad, C. (2011). Brain correlates of hypnotic paralysis-a resting-state fMRI study. *Neuroimage, 56*(4), 2173-2182. doi:10.1016/j.neuroimage.2011.03.078

Raz, A., Fan, J., & Posner, M. I. (2005). Hypnotic suggestion reduces conflict in the human brain. *Proceedings of the National Academy of Sciences of the United States of America, 102*(28), 9978-9983. doi:10.1073/pnas.0503064102

Raz, A., Kirsch, I., Pollard, J., & Nitkin-Kaner, Y. (2006). Suggestion reduces the stroop effect. *Psychological Science, 17*(2), 91-95. doi:10.1111/j.1467-9280.2006.01669.x

Raz, A., Landzberg, K. S., Schweizer, H. R., Zephrani, Z. R., Shapiro, T., Fan, J., & Posner, M. I. (2003). Posthypnotic suggestion and the modulation of Stroop interference under cycloplegia. *Consciousness and Cognition, 12*(3), 332-346. doi:10.1016/s1053-8100(03)00024-2

Reinhart, R. M. G., & Nguyen, J. A. (2019). Working memory revived in older adults by synchronizing rhythmic brain circuits. *Nature Neuroscience, 22*(5), 820-827. doi:10.1038/s41593-019-0371-x

Rosenthal, D. M. (2002). How many kinds of consciousness? *Consciousness and Cognition, 11*(4), 653-665. doi:10.1016/s1053-8100(02)00017-x

Rosenthal, D. M. (2006). Consciousness and Higher‐Order Thought. *Encyclopedia of cognitive science*. doi:10.1002/0470018860.s00149

Rottschy, C., Langner, R., Dogan, I., Reetz, K., Laird, A. R., Schulz, J. B., . . . Eickhoff, S. B. (2012). Modelling neural correlates of working memory: a coordinate-based meta-analysis. *Neuroimage, 60*(1), 830-846. doi:10.1016/j.neuroimage.2011.11.050

Ruitenberg, M. F., De Kleine, E., Van der Lubbe, R. H., Verwey, W. B., & Abrahamse, E. L. (2012). Context-dependent motor skill and the role of practice. *Psychological Research, 76*(6), 812-820. doi:10.1007/s00426-011-0388-6

Saalmann, Y. B., & Kastner, S. (2009). Gain control in the visual thalamus during perception and cognition. *Current Opinion in Neurobiology, 19*(4), 408-414. doi:10.1016/j.conb.2009.05.007

Schoenberger, N. E. (2000). Research on hypnosis as an adjunct to cognitive-behavioral psychotherapy. *International Journal of Clinical and Experimental Hypnosis, 48*(2), 154-169. doi:10.1080/00207140008410046

Semmens-Wheeler, R., Dienes, Z., & Duka, T. (2013). Alcohol increases hypnotic susceptibility. *Consciousness and Cognition, 22*(3), 1082-1091. doi:10.1016/j.concog.2013.07.001

Sheehan, P. W., Donovan, P., & MacLeod, C. M. (1988). Strategy manipulation and the Stroop effect in hypnosis. *Journal of Abnormal Psychology, 97*(4), 455-460. doi:10.1037/0021-843x.97.4.455

Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory. *Psychological Bulletin, 136*(6), 943-974. doi:10.1037/a0020541

Shor, R. E., & Orne, E. C. (1962). *Harvard group scale of hypnotic susceptibility*: Consulting Psychologists Press.

Shor, R. E., & Orne, E. C. (1963). Norms on the Harvard group scale of hypnotic susceptibility, form A. *International Journal of Clinical and Experimental Hypnosis, 11*, 39-47. doi:10.1080/00207146308409226

Spanos, N. P. (1971). Goal-directed fantasy and the performance of hypnotic test suggestions. *Psychiatry, 34*(1), 86-96. doi:10.1080/00332747.1971.11023658

Spanos, N. P., & Barber, T. X. (1968). " Hypnotic" experiences as inferred from subjective reports: Auditory and visual hallucinations. *Journal of Experimental Research in Personality*.

Spanos, N. P., Cobb, P. C., & Gorassini, D. R. (1985). Failing to resist hypnotic test suggestions: a strategy for self-presenting as deeply hypnotized. *Psychiatry, 48*(3), 282-292. doi:10.1080/00332747.1985.11024288

Srzich, A. J., Cirillo, J., Stinear, J. W., Coxon, J. P., McMorland, A. J. C., & Anson, J. G. (2019). Does hypnotic susceptibility influence information processing speed and motor cortical preparatory activity? *Neuropsychologia, 129*, 179-190. doi:10.1016/j.neuropsychologia.2019.03.014

Stefanidis, D., Anton, N. E., Howley, L. D., Bean, E., Yurco, A., Pimentel, M. E., & Davis, C. K. (2017). Effectiveness of a comprehensive mental skills curriculum in enhancing surgical performance: Results of a randomized controlled trial. *American Journal of Surgery, 213*(2), 318-324. doi:10.1016/j.amjsurg.2016.10.016

Strahan, E. J., Spencer, S. J., & Zanna, M. P. (2002). Subliminal priming and persuasion: Striking while the iron is hot. *Journal of Experimental Social Psychology, 38*(6), 556-568. doi:10.1016/s0022-1031(02)00502-4

Szechtman, H., Woody, E., Bowers, K. S., & Nahmias, C. (1998). Where the imaginal appears real: a positron emission tomography study of auditory hallucinations. *Proceedings of the National Academy of Sciences of the United States of America, 95*(4), 1956-1960. doi:10.1073/pnas.95.4.1956

Terhune, D. B., & Cardena, E. (2016). Nuances and Uncertainties Regarding Hypnotic Inductions: Toward a Theoretically Informed Praxis. *American Journal of Clinical Hypnosis, 59*(2), 155-174. doi:10.1080/00029157.2016.1201454

Terhune, D. B., & Cardeña, E. (2010). Differential patterns of spontaneous experiential response to a hypnotic induction: A latent profile analysis. *Consciousness and Cognition, 19*(4), 1140-1150. doi:10.1016/j.concog.2010.03.006

Terhune, D. B., Cardena, E., & Lindgren, M. (2011). Dissociative tendencies and individual differences in high hypnotic suggestibility. *Cognitive Neuropsychiatry, 16*(2), 113-135. doi:10.1080/13546805.2010.503048

Terhune, D. B., Cleeremans, A., Raz, A., & Lynn, S. J. (2017). Hypnosis and top-down regulation of consciousness. *Neuroscience and Biobehavioral Reviews, 81*(Pt A), 59-74. doi:10.1016/j.neubiorev.2017.02.002

Terhune, D. B., & Hedman, L. R. A. (2017). Metacognition of agency is reduced in high hypnotic suggestibility. *Cognition, 168*, 176-181. doi:10.1016/j.cognition.2017.06.026

Thompson, T., Terhune, D. B., Oram, C., Sharangparni, J., Rouf, R., Solmi, M., . . . Stubbs, B. (2019). The effectiveness of hypnosis for pain relief: A systematic review and meta-analysis of 85 controlled experimental trials. *Neuroscience and Biobehavioral Reviews, 99*, 298-310. doi:10.1016/j.neubiorev.2019.02.013

Tobis, I. P., & Kihlstrom, J. F. (2010). Allocation of attentional resources in posthypnotic suggestion. *International Journal of Clinical and Experimental Hypnosis, 58*(4), 367-382. doi:10.1080/00207144.2010.499330

Ulrich, M., Kiefer, M., Bongartz, W., Gron, G., & Hoenig, K. (2015). Suggestion-Induced Modulation of Semantic Priming during Functional Magnetic Resonance Imaging. *PloS One, 10*(4), e0123686. doi:10.1371/journal.pone.0123686

Valentine, K. E., Milling, L. S., Clark, L. J., & Moriarty, C. L. (2019). The Efficacy of Hypnosis as a Treatment for Anxiety: A Meta-Analysis. *International Journal of Clinical and Experimental Hypnosis, 67*(3), 336-363. doi:10.1080/00207144.2019.1613863

van der Graaf, F. H., Maguire, R. P., Leenders, K. L., & de Jong, B. M. (2006). Cerebral activation related to implicit sequence learning in a Double Serial Reaction Time task. *Brain Research, 1081*(1), 179-190. doi:10.1016/j.brainres.2006.01.103

Vanhaudenhuyse, A., Boly, M., Balteau, E., Schnakers, C., Moonen, G., Luxen, A., . . . Faymonville, M. E. (2009). Pain and non-pain processing during hypnosis: a thulium-YAG event-related fMRI study. *Neuroimage, 47*(3), 1047-1054. doi:10.1016/j.neuroimage.2009.05.031

Wager, T. D., & Smith, E. E. (2003). Neuroimaging studies of working memory: a meta-analysis. *Cognitive, Affective & Behavioral Neuroscience, 3*(4), 255-274. doi:10.3758/cabn.3.4.255

Walsh, E., Oakley, D. A., Halligan, P. W., Mehta, M. A., & Deeley, Q. (2015). The functional anatomy and connectivity of thought insertion and alien control of movement. *Cortex, 64*, 380-393. doi:10.1016/j.cortex.2014.09.012

Warrington, E. K., & Shallice, T. (1980). Word-form dyslexia. *Brain, 103*(1), 99-112. doi:10.1093/brain/103.1.99

Weitzenhoffer, A. M., & Hilgard, E. R. (1962). *Stanford hypnotic susceptibility scale, form C* (Vol. 27). Palo Alto, CA: Consulting Psychologists Press.

Whittlesea, B. W. (2002a). False memory and the discrepancy-attribution hypothesis: the prototype-familiarity illusion. *Journal of Experimental Psychology: General, 131*(1), 96-115. doi:10.1037//0096-3445.131.1.96

Whittlesea, B. W. (2002b). Two routes to remembering (and another to remembering not). *Journal of Experimental Psychology: General, 131*(3), 325-348. doi:10.1037//0096-3445.131.3.325

Woody, E., & Szechtman, H. (2000). Hypnotic hallucinations: towards a biology of epistemology. *Contemporary Hypnosis, 17*(1), 4-14. doi:10.1002/ch.186

Woody, E. Z., & Barnier, A. J. (2008). Hypnosis scales for the twenty-first century: What do we need and how should we use them. *The Oxford handbook of hypnosis: Theory, research, and practice*, 255-282.

Woody, E. Z., Barnier, A. J., & McConkey, K. M. (2005). Multiple hypnotizabilities: differentiating the building blocks of hypnotic response. *Psychological Assessment, 17*(2), 200-211. doi:10.1037/1040-3590.17.2.200

Woody, E. Z., & Bowers, K. S. (1994). *A frontal assault on dissociated control*: Guilford Press New York.

Yon, D., de Lange, F. P., & Press, C. (2019). The Predictive Brain as a Stubborn Scientist. *Trends in Cognitive Sciences, 23*(1), 6-8. doi:10.1016/j.tics.2018.10.003

Zahedi, A., Abdel Rahman, R., Sturmer, B., & Sommer, W. (2019). Common and specific loci of Stroop effects in vocal and manual tasks, revealed by event-related brain potentials and posthypnotic suggestions. *Journal of Experimental Psychology: General, 148*(9), 1575-1594. doi:10.1037/xge0000574

Zahedi, A., Luczak, A., & Sommer, W. (2020). Modification of food preferences by posthypnotic suggestions: An event-related brain potential study. *Appetite, 151*, 104713. doi:10.1016/j.appet.2020.104713

Zahedi, A., Stuermer, B., Hatami, J., Rostami, R., & Sommer, W. (2017). Eliminating stroop effects with post-hypnotic instructions: Brain mechanisms inferred from EEG. *Neuropsychologia, 96*, 70-77. doi:10.1016/j.neuropsychologia.2017.01.006

Zahedi, A., Sturmer, B., & Sommer, W. (2020). Can posthypnotic suggestions boost updating in working memory? Behavioral and ERP evidence. *Neuropsychologia, 148*, 107632. doi:10.1016/j.neuropsychologia.2020.107632

Zamansky, H. S., & Clark, L. E. (1986). Cognitive competition and hypnotic behavior: whither absorption? *International Journal of Clinical and Experimental Hypnosis, 34*(3), 205-214. doi:10.1080/00207148608406986

Is there a G-factor in Hypnotic Suggestibility? Confirmatory Factor Analysis of the Harvard Group Scale of Hypnotic Suggestibility

Anoushiravan Zahedi*, Werner Sommer

Department of Psychology, Humboldt-Universitat zu Berlin, Rudower Chaussee 18, 12489, Berlin, Germany

Author Note

* Corresponding Author; Institut für Psychologie, Humboldt-Universität zu Berlin, Rudower Chaussee 18, 12489, Berlin, Germany.

E-mail address: zahedian@hu-berlin.de

Acknowledgment

This work was supported by a scholarship to A.Z. by the Deutscher Akademischer Austauschdienst (DAAD).

Data and Supplementary Materials

For accessing raw data, model descriptions, and R-codes, please see: https://osf.io/dus9e/?view_only=a49b581910124673abf3e3e3b24454f5

Abstract

Undisputedly, individuals differ substantially in their responsiveness to hypnotic and posthypnotic suggestions. However, defining and measuring hypnotizability is contentious. Standardized measures of "hypnotic susceptibility" do not measure hypnotizability per se, but instead, a mixture of general suggestibility (i.e., the ability to respond to suggestions independent of hypnosis) and hypnotizability (i.e., the increase of suggestibility due to hypnotic induction). This mixture can be called hypnotic-suggestibility. Indeed, exploratory factor analyses (EFA) of standardized scales found them to be heterogeneous. However, the number and nature of the latent factors are a matter of debate. Here, we applied confirmatory factor analysis to the scores of the Harvard group scale of hypnotic susceptibility (HGSHS) obtained from 477 volunteers. Several theory-driven models were tested, most notably a three-factor model, corresponding to previous results from EFA, and a bifactor model. HGSHS scores were best explained by the bifactor model consisting of a G-factor tapping into hypnotizability and three specific grouping factors measuring different suggestibilities, each requiring a unique combination of three top-down cognitive functions: cognitive-simulation, sensory-adaptation, and problem-solving. Further, structural equation modeling of causal pathways between latent factors revealed that the outcome of the suggestions, requiring a combination of cognitive-simulation and sensory-adaptation, can predict responses to other suggestions. The present results indicate the complex, multifaceted structure of hypnotic suggestibility and underscore the need for developing a new scale of hypnotic-suggestibility, focused on simulation-adaptation suggestions for clinical and research purposes, and revisiting applications of traditional standardized scales.

Keywords: Confirmatory factor analyses, Structural equation modeling (SEM), Hypnosis, Suggestibility, Hypnotizability.

Is there a G-factor in Hypnotic Suggestibility? Confirmatory Factor Analysis of the Harvard Group Scale of Hypnotic Suggestibility

1. Introduction

Historically, hypnosis has been explained by two main alternative accounts. The state approach defines hypnosis as an altered state of consciousness similar to yoga or meditation (Elkins, Barabasz, Council, & Spiegel, 2015). In contrast, the socio-cognitive account (Kirsch & Lynn, 1998; Lynn & Green, 2011; Lynn, Rhue, & Weekes, 1990) emphasizes cognitive, social, and psychological variables involved in responding to hypnotic suggestions (Spanos, 1971; Spanos, Cobb, & Gorassini, 1985). As discussed by Jensen et al. (2015) and Lynn and Green (2011), contemporary theories of hypnosis only partially align with these traditional alternative views (for review, see Zahedi & Sommer, 2021) and no consensus has been reached. Independent of ongoing disputes, theories of hypnosis agree on the existence of substantial within- and between-subject variability in responding to hypnotic and posthypnotic suggestions (Shor & Orne, 1963). However, defining and measuring hypnotizability is a more contentious issue. Two approaches can be distinguished.

First, based on studies (e.g., Braffman & Kirsch, 1999; e.g., Mazzoni et al., 2009; McGeown et al., 2012; Palfi, Parris, McLatchie, Kekecs, & Dienes, 2020; Parris & Dienes, 2013) that have shown strong correlations between responding to suggestions inside and outside of hypnosis ($r = .67$ for behavioral scores; $r = .82$ for subjective scores; Braffman & Kirsch, 1999), Kirsch (1997) concluded that suggestibility and hypnotizability should be separated. He distinguished (I) *suggestibility* as the capability to respond to suggestions regardless of hypnosis, (II) *hypnotic-suggestibility* as the capability to respond to suggestions under the influence of hypnosis, and finally, (III) *hypnotizability* as the increase in suggestibility due to induction of hypnosis (i.e., the difference between hypnotic-suggestibility and suggestibility). Unfortunately, as yet, this sophisticated definition of hypnotizability has not been translated into a reliable and valid hypnotizability scale.

Alternatively, one might define hypnotizability as what standardized scales of hypnotizability are measuring. Noteworthy, in this definition, hypnotizability is equated with hypnotic-suggestibility in terms of Kirsch's (1997) description of hypnotizability. Two of the most commonly employed hypnotic-suggestibility scales are the Sandford scale of hypnotic susceptibility (SSHS; Weitzenhoffer & Hilgard, 1962) and the Harvard group scale of hypnotic susceptibility (HGSHS; Shor & Orne, 1962; Shor & Orne, 1963). These two scales are similar in nature, except that the HGSHS is designed for group administration, whereas the SHSS is designed for individual-participant administration. In both scales, a range of suggestions is presented consecutively, and in the end, either participants themselves (in the HGSHS) or administrators (in the SHSS) determine how many of the suggestions had been executed. Hence, participants can receive a score between 0-12 in the HGSHS and 0-11 in the SHSS. Based on their hypnotic-suggestibility scores, participants are conventionally categorized as high-, medium-, and low-suggestibles. For instance, in the HGSHS, participants with $scores \geq 9$, $8 \geq scores \geq 5$, and $4 \geq scores$ are considered high-, medium-, and low-hypnotic-suggestible, respectively. Both scales are very stable over time; for instance, for the HGSHS scores, stability coefficients of $.82\ (15 - year\ retest)\ and\ .71\ (25 - year\ retest)$ have been reported (Piccione, Hilgard, & Zimbardo, 1989).

However, these scales are not flawless. The internal consistency of the HGSHS is at best just acceptable (e.g., Bongartz, 1985; Peter et al., 2014; Robin, Kumar, & Pekala, 2005; Varga, Farkas, & Mero, 2012). A related problem is the heterogeneity of standardized scales aiming to measure hypnotic-suggestibility. For instance, several previous studies scrutinized the structure of HGSHS scores (e.g., McConkey, Sheehan, & Law, 1980; Oakman & Woody, 1996; Piesbergen & Peter, 2006; Woody, Barnier, & McConkey, 2005) and SSHS scores (e.g., Woody et al., 2005) by conducting exploratory factor analyses (EFA). Based on these studies, a strong consensus has been reached that the HGSHS items do not represent only a single factor. However, there is less consensus about the number and nature of latent factors involved. There is a tentative consensus that the HGSHS items are measuring at least three latent factors (Tab. 1). The first latent factor is characterized by ideomotor suggestions, such as "soon after thinking of your head falling forward, you feel a tendency to make the movement." The second factor consists of so-called challenge suggestions, such as "your hands feel heavy… too heavy to be lifted". And the third factor is related to cognitive suggestions such as "you will be increasingly aware of a fly that is going round and round about your head." However, the third factor is very loosely defined, and in EFA, sometimes only one suggestion is loading on this factor (e.g., McConkey et al., 1980).

Why is there only a weak consensus about the number and nature of latent factors in the HGSHS? All previous studies investigating the structure of hypnotizability scales have utilized EFA (e.g., McConkey et al., 1980; Oakman & Woody, 1996; Piesbergen & Peter, 2006). Even though EFA is an essential and necessary step, it has limitations. These limitations can be overcome by confirmatory factor analysis (CFA) and structural equation modeling (SEM) (Coulacoglou & Saklofske, 2017). (1) In EFA, no explicit theory-driven hypotheses are formulated and tested. Therefore, the interpretation of the derived factors are post hoc and may vary across studies (Coulacoglou & Saklofske, 2017; Harrington, 2009). In contrast, CFA is theory-driven, and factors are defined a priori. Therefore, we hold that the data-driven nature of EFA is the main reason why results from EFA do not converge on the number and theoretical explanations of latent factors.

Consequently, the present study will apply CFA and SEM for investigating the homogeneity and structure of the HGSHS (Coulacoglou & Saklofske, 2017; Harrington, 2009) as a canonical example of hypnotic-suggestibility scales. (2) Even though EFAs have shown that variance in the items of the HGSHS must be explained by more than one factor, it is unclear whether a model, which, in addition to specific grouping factors, also assumes a general factor (G-factor) of hypnotizability, will explain the data better than a simple multifactor model. Of particular interest for addressing this question is bifactor modeling (Reise, 2012), which can be implemented only in CFA but not EFA. Bifactor models have addressed long-standing questions, from personality psychology (Musek, 2017) to neuroimaging of individual differences (Cooper, Jackson, Barch, & Braver, 2019) and probably most noticeably in psychometric and intelligence research (Eid, Krumm, Koch, & Schulze, 2018). (3) Finally, SEM allows us to explore causal relationships between latent variables. Thus, SEM of HGSHS factors can address whether there is a special grouping factor to which other grouping factors regress. Using SEM, we will test whether responsiveness to a certain group of suggestions (as a latent variable) can predict how participants respond to other suggestions at the level of latent factors. Causality pathway testing is only interpretable when hypotheses are theory-driven and formulated a priori and, therefore, only applicable in conjunction with CFA. Summarizing, several important questions, namely, the number and nature of factors, the existence of a G-factor, and causal pathways between latent factors, can be addressed best by conducting CFA and SEM, which is the general aim of the present paper.

A vital prerequisite to formulating relevant hypotheses for CFA is an appropriate theory. Based on the separable categories of suggestions found by EFAs, Woody et al. (2005) concluded that there are multiple hypnotizabilities. The most straightforward theoretical interpretation of multiple hypnotizabilities is to assume distinguishable cognitive mechanisms underlying the different categories of suggestions. However, only three hypnosis theories make such assumptions (for review, see Zahedi & Sommer, 2021)

The first theory is the *unified cognitive theory* (Brown & Oakley, 2004), which is grounded on the concept of contention scheduling (Norman & Shallice, 1986). Norman and Shallice (1986) assume two separable control systems to be involved in action production, that is, the supervisory attentional system (SAS) and contention scheduling (CS). The SAS will interfere when the existing response repertoire is not sufficient for handling a situation or task. In these cases, either a new schema (i.e., a stimulus-response contingency) must be created, or a well-established (prepotent) schema should be inhibited in favor of a less-established schema. In situations that need less cognitive control and can be handled by existing response repertoire, different sets of potential "source schemata" may compete with each other, and the schema that first exceeds a certain activation threshold will be selected by CS (Norman & Shallice, 1986). Brown and Oakley (2004) defined two mutually exclusive styles of responding to hypnotic suggestions, namely, constructive and concentrative. In the concentrative style, the SAS will be disabled or decoupled, and therefore, cannot be used for responding to suggestions. Hence, CS will be the only system in charge of action control. In contrast, in the constructive style, goal-directed imagination, requiring the SAS, will be used for responding to hypnotic suggestions. Even though the unified cognitive theory and its two response styles can be used to understand between-subject differences in responding to suggestions, it does not explain within-subject variance. Therefore, one cannot employ the unified cognitive theory for interpreting the existence of multiple hypnotizabilities within individuals.

The second theory is the *cold control* theory (Dienes et al., 2009; Dienes & Perner, 2007). According to the higher-order thoughts theory (Rosenthal, 2002; Rosenthal, 2006; Rosenthal, 2008), the cold control theory delineates perception and awareness of perception by being attributed to different levels of higher-order thoughts. First-order thoughts, such as “I see a cat,” are related to perception. Second-order thoughts, however, refer to being aware of perception, that is, “I am aware that I see a cat.” Finally, third-order thoughts designate consciousness of being aware of perception, that is, “I know that I am aware of seeing a cat.” In their cold control theory, Dienes and Perner (2007) proposed that the underlying mechanism of responding to suggestions is the distortion of higher-order thoughts. More specifically, medium-hypnotizable participants are capable of blocking third-order thoughts, whereas high-hypnotizables can inhibit both second- and third-order thoughts. The main prediction of the cold control theory is that the decoupling or disabling of brain areas related to ascriptive metacognition, that is, (left) dorsolateral prefrontal cortex (DLPFC) (Miele, Wager, Mitchell, & Metcalfe, 2011), is necessary for responding to hypnotic and posthypnotic suggestions. Although higher responsiveness to suggestions - based on subjective reports – could be induced by the disabling of DLPFC by alcohol consumption (Semmens-Wheeler, Dienes, & Duka, 2013) or transcranial magnetic stimulation (TMS) (Dienes & Hutton, 2013), there was no such effect in objective scores. Many other studies show that responding to suggestions is related to (I) increased DLPFC activation (e.g., Cojan, Archimi, Cheseaux, Waber, & Vuilleumier, 2013; Cojan et al., 2009; Ludwig et al., 2015; Pyka et al., 2011), (II) the implementation of cognitive functions, such as executive functions, that require activation of DLPFC (Palfi et al., 2020; Zahedi, Abdel Rahman, Sturmer, & Sommer, 2019; Zahedi, Sturmer, & Sommer, 2020), or (III) is unrelated to changes in DLPFC activation (e.g., Egner & Raz, 2007; Landry, Lifshitz, & Raz, 2017). Therefore, the observed results do not support the prediction that suggestibility is related to the disruption of DLPFC activity. A second tenet of the cold control theory is the distinction between suggestions inducing the blocking of only third-order thoughts and suggestions that require blockage of both third- and second-order thoughts. However, as discussed above, there are at least three categories of suggestions, which can be robustly separated by EFAs (McConkey et al., 1980; Woody et al., 2005). Furthermore, challenge and cognitive suggestions cannot be distinguished on the basis of the cold control theory. Because, for successfully responding to both kinds of suggestions, that is, exerting the suggested action and simultaneously not attributing it to direct volitional effort (Kihlstrom, 2008; Lynn et al., 1990), one reasonably needs to block both second- and third-order thoughts.

The third hypnosis theory is the *simulation-adaptation theory of hypnosis* (SATH; Zahedi & Sommer, 2021) which incorporates three concepts. The first concept is cognitive-simulation, suggesting that imagining a stimulus has the same effects as perceiving that stimulus (Farah, 1988). The main difference between imagining and perceiving is that the former, in contrast to the latter, is caused by inner thoughts rather than external stimuli (Hesslow, 2002). For instance, imagining a stimulus not only activates the same brain areas but also causes the same responses as perceiving the corresponding stimulus (for review, see Hesslow, 2002). The second concept is top-down regulation of sensory input (Frank, 2016; Lopresti-Goodman, Turvey, & Frank, 2013), suggesting if mental representations of stimuli are generated and cognitively manipulated, the perception of such stimuli is subjected to top-down adaptation. In other words, forming mental representations of stimuli, between perceiving and responding to them, allows for top-down downregulation of sensory input. For example, if participants are asked to judge whether they need one or two hands for lifting planks of different sizes while they either grasp them or only look at them, the latter condition but not the former will be subjected to top-down sensory-adaptation (Lopresti-Goodman et al., 2013). The third concept is predictive coding (Friston, 2010), which suggests that any action, that is, motion or perception, will be initiated by forming predictions about the next state of the motor and/or sensory apparatus (Adams, Shipp, & Friston, 2013; Clark, 2013). Next, predictions are propagated downward through cortico-cortical and corticospinal projections to the relevant muscles and sensory units. Notably, down propagating signals are always *predictions* and not *motor commands* (for the treatment of neuromuscular mechanisms, see Adams et al., 2013). If there will be a difference between the state of the system and the prediction, a prediction error is formed (i.e., being in the surprise state). Any self-organizing system aims to reside in the lowest possible energy state. Therefore, in the surprised-state, such systems attempt to minimize prediction errors (Friston, 2010). During volitional movements, predictions have a higher weight in comparison to prediction errors. Consequently, to leave the surprise-state, prediction errors are used in reflex arcs to correct the movement and align it with predictions. Hence, prediction errors are gradually downregulated in reflex arcs during backpropagation and are diminished sufficiently to be not propagated beyond thalamic nuclei (Adams et al., 2013; Brown, Adams, Parees, Edwards, & Friston, 2013). During perception, on the other hand, prediction errors are given a higher weight compared to predictions. Hence, this time, predictions are updated based on prediction errors for coming out of the surprised-state. In predictive coding theory, these two processes are called active and perceptual inference, respectively. Despite its popularity and success in explaining normal perception and action, predictive coding cannot explain, why during hypnosis, participants can execute actions described by suggestions but attribute the action to external sources, that is, perceive them to be caused externally rather than by their own volition (Lynn et al., 1990). In terms of the predictive coding model, to start a movement, predictions must be given a higher weight than sensory feedback from the external world (i.e., active inference); however, participants will only perceive their response as externally originated if prediction errors have a higher weight than predictions (i.e., perceptual inference) (Brown et al., 2013; Clark, 2013).

SATH employs three top-down cognitive processes to explain hypnotic and posthypnotic suggestion-induced responses; these processes are used to different extents and in various combinations, depending on the individual's capabilities. (1) *Cognitive-simulation* (Farah, 1988; Hesslow, 2002). During hypnosis, participants have two sources of input, imagination and the external world. In other words, besides perceptual input from the external world, stimuli described by suggestions that are imagined by participants provide "perceptual" input from mental imagery. (2) *Sensory-adaptation* (Frank, 2016; Lopresti-Goodman et al., 2013). When sensory input from external stimuli is not aligned with imaginations and suggestions, sensory-adaption may downregulate perceptual input from the external world. Together with predictive coding, cognitive-simulation and sensory-adaptation can explain why hypnotized participants execute responses and attribute them to external sources. During hypnosis, imaginations are given higher weight in comparison to predictions. Hence, predictions are updated based on perceptual input from imaginations (perceptual inference). Simultaneously, predictions are given a higher weight in comparison to sensory input. Therefore, sensory input from the external world is used in reflex arcs to align movements with predictions (active inference) and simultaneously downregulated by top-down sensory-adaptation preventing it from passing beyond thalamic nuclei. Consequently, hypnotized participants exert a suggested motion and simultaneously attribute it to the suggestions (or external sources) rather than to themselves. (3) *Mental practice and problem-solving* (Zahedi, Sturmer, et al., 2020). There are two situations that cannot be explained with cognitive-simulation and sensory-adaption and, as a result, require a further cognitive top-down process. (I) When suggestions do not provide imagery-provoking descriptions of stimuli, hypnotized participants need to fill in the gap and find an appropriate imagination (i.e., strategy) for cognitive-simulation. (II) In case that suggestions aim to form a new trigger-response contingency, cognitive-simulation can provide an (imagined) exercise environment, where new strategies, either outlined by suggestions or developed by participants themselves, are mentally practiced.

According to SATH, besides the aforementioned top-down cognitive processes, social and psychological factors may also be of great importance. As all the top-down processes above are volitional and goal-directed, participants' expectations, openness, and willingness will determine whether they will be motivated to engage in the responses described in the suggestions.

1.1. Theory-driven Hypotheses for CFA and SEM

In the present study, we used SATH as a framework to formulate theory-driven hypotheses to be tested by CFA and SEM. Based on SATH, a bifactor model should best explain the variance in HGSHS scores. The proposed bifactor model consists of a G-factor and three grouping factors, as will be justified next and illustrated in Figure 1.

The first grouping factor covers simulation suggestions, where sensory information is congruent with the portrayed response (Fig. 1A). For instance, consider the suggestion: "stretch your arm and keep it in the air, after a while your hand starts to feel fatigued and it starts to move downward. It is as if a heavyweight has been put on your arm" (Shor & Orne, 1962). Here, sensory input is aligned with the suggestion; if participants stretch their arms, they will feel fatigued after a while. Therefore, the suggestion predicts a sensation that will indeed occur. Nonetheless, if the suggestion is successful, the fatigue will not be attributed to body-internal processes (Kihlstrom, 2008; Lynn et al., 1990) but to the hypnotic condition. This will only happen if participants imagine what is described by simulation suggestions (i.e., a heavyweight is put on their arm). Hence, cognitive-simulation is necessary for successful exertion of targeted hypnotic-suggestion-induced responses.

The second group of suggestions can be described as simulation-adaptation suggestions (Fig. 1B). In these suggestions, sensory information is incongruent or conflicting with the suggested information. For instance, consider the hand levitation suggestion: your hand feels lighter “as if there's a large helium balloon under [your] palm, or attached with strings to each [one of your] fingertip and [your] wrist … [your] hand and arm will begin to float up” (Hammond, 1998, pp. 43-44). As explained by SATH, when sensory input is not aligned with imagination, it is downregulated through the top-down mechanism of sensory-adaptation. Together, cognitive-simulation and sensory-adaptation can explain why the motion described in the suggestion is executed by the hypnotized participant, but nevertheless, attributed to an external cause. Let’s consider the hand levitation suggestion. Here, predictions are generated based on cognitive-simulation of the suggestions’ description (i.e., helium balloons are attached to the fingers). Since the predictions (i.e., the hand and arm will be levitated) will receive a lower weight than the imaginary input, they are updated based on prediction errors formed from the comparison of predictions with cognitive-simulation feedback. This explains why the motion is attributed to an external source or cause (i.e., helium balloons). At the same time, predictions will be given a higher weight compared to sensory feedback, which is downregulated by top-down sensory-adaptation. Consequently, the targeted motion is executed, and sensory feedback will be used for adapting the movement with predictions. Evidently, in simulation-adaptation suggestions, besides cognitive-simulation, sensory-adaptation must be incorporated. This fact distinguishes this category from mere simulation suggestions, where only cognitive-simulation is necessary.

The third grouping factor relates to suggestions that require executive functions, for example, in order to find appropriate imagery for cognitive-simulation, forming a new trigger-response contingency, or adapting an existing response to a novel situation. In the most common cases, an executive function suggestion will only describe a goal but no concrete strategy for accomplishing the goal, and participants are responsible for filling the gap. That is, participants have to find an appropriate cognitive strategy and then implement the necessary mechanisms for executing this strategy. Importantly, after finding a suitable strategy for complying with a suggestion, the suggestion will turn into a simulation or simulation-adaptation suggestion (Fig. 1C). Consider, for example, the posthypnotic suggestion item of HGSHS: after the termination of hypnosis, “when you hear a tapping noise, you will reach down and touch your ankle” (Shor & Orne, 1962). The suggestion has clearly defined the goal but no strategy for implementing it. If participants merely reach down and touch their ankle while believing that they are doing this because the suggestion instructed or commanded them to do so, the action will be attributed to the exertion of direct volitional effort. However, in an alternative scenario, if participants imagine the sound and repeatedly connect it to itching or burning in their ankle, they will exert the portrayed action after hearing the sound but will not attribute it to any volitional effort of their own. Any suggestion can be an executive function suggestion if it fails to imply an applicable strategy for the suggested action. This notion has been confirmed by Galea, Woody, Szechtman, and Pierrynowski (2010). In their study, first, high-hypnotic-suggestible participants were given a suggestion, aiming to induce rigidity and stiffness in their arms. Afterward, participates were asked to move their arms with the implication that they cannot do it. The authors intentionally did not present a relevant strategy, for instance, believing to be paralyzed. As inferred by electromyography, the participants of Galea et al. (2010) came up with different strategies, such as simultaneously activating agonist and antagonist muscles (biceps and triceps), only activating the antagonist (triceps) but inactivating the agonist, or not activating any muscle.

Another form of executive function suggestion covers situations where participants are directly asked to mentally practice a strategy until it becomes semi-automatic. This form of suggestions has been repeatedly employed in studies that sought to enhance performance in different cognitive tasks (e.g., Iani, Ricci, Baroni, & Rubichi, 2009; Iani, Ricci, Gherri, & Rubichi, 2006; Raz, Fan, & Posner, 2005; Raz, Kirsch, Pollard, & Nitkin-Kaner, 2006; Zahedi et al., 2019; Zahedi, Luczak, & Sommer, 2020; Zahedi, Stuermer, Hatami, Rostami, & Sommer, 2017; Zahedi, Sturmer, et al., 2020). However, as no relevant suggestion is included in the HGSHS or SSHS, we will not discuss it further.

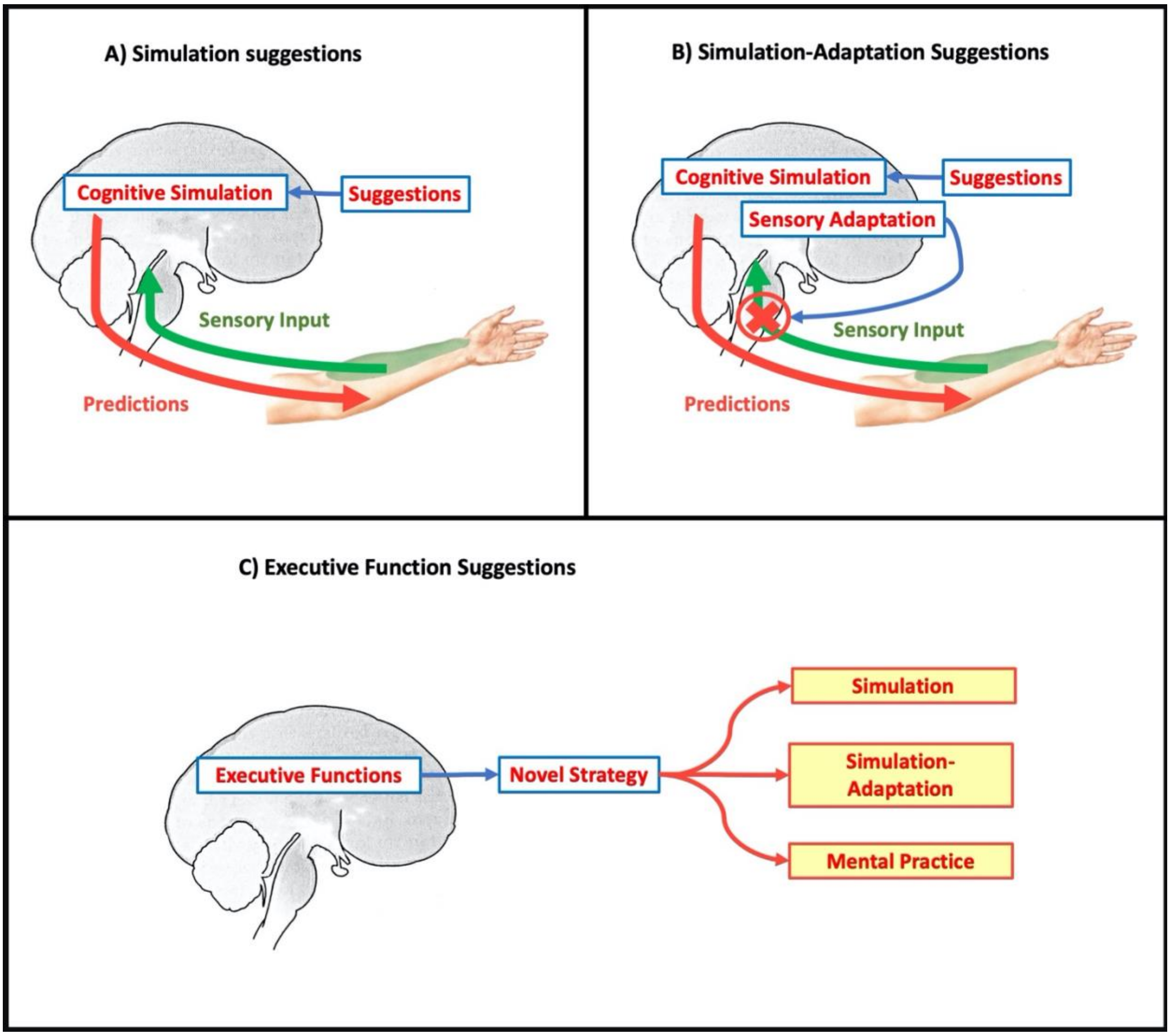


Figure 1. Schematic representation of different kinds of hypnotic and post-hypnotic suggestions and the hypothetical underlying processes; A) simulation, B) simulation-adaptation, and C) executive function suggestions. For details, please see text.

Based on SATH (c.f., Zahedi & Sommer, 2021), we assume that simple multifactor models are not adequate for explaining the variance in hypnotic-suggestibility scales. Instead, two alternatives to the multifactor model presented in Table 1 can be proposed. First, in contrast to other top-down cognitive processes required for responding to suggestions, SATH assumes that cognitive-simulation is needed to successfully execute all types of suggestions presented in the HGSHS. This proposition is corroborated by the meta-analysis of Landry et al. (2017), which showed that imagination is the shared characteristic of many different forms of suggestions. Hence, one might expect, treating the cognitive-simulation factor (i.e., a grouping factor) as a G-factor should improve the multifactor model.

The second model focuses on SATH's hypothesis that there are two sources of variability in hypnotic-suggestibility, echoing the proposition of Kirsch (1997), asserting that hypnotic-suggestibility can be decomposed into general suggestibility (capability of responding to suggestions regardless of hypnosis) and hypnotizability (increase in suggestibility due to hypnotic induction). Hence, besides the specific correlated grouping factors, capturing the different suggestibilities described above (related to different top-down cognitive processes), one may expect that the addition of a general factor to which all HGSHS items contribute will improve the model. Evidently, two G-factors are included in this model. That is, the suggestibility G-factor, measured by the correlated grouping factors, and the G-factor of hypnotizability, capturing the psychosocial variables involved in responding to hypnotic suggestions (i.e., hypnotizability). Notably, the G-factor of hypnotizability is unrelated to cognitive processes involved in responding to suggestions (i.e., the suggestibilities).

Table 1. Categorization of the suggestions in HGSHS-A into three proposed specific factors and the results of exploratory factor analysis (EFA, McConkey et al., 1980)

Suggestions	Proposed Specific Factor	EFA [a]
1. HEAD FALLING	S	2.Ideomotor
2. EYE CLOSURE	S	2.Ideomotor
3. HAND LOWERING (LEFT HAND)	S	2.Ideomotor
4. ARM IMMOBILIZATION (RIGHT ARM)	SA	1.Challenge
5. FINGER LOCK	SA	1.Challenge
6. ARM RIGIDITY (LEFT)	SA	1.Challenge
7. MOVING HANDS TOGETHER	S	2.Ideomotor
8. COMMUNICATION INHIBITION	SA	1.Challenge
9. EXPERIENCING OF A FLY	EF	3.Cognitive
10. EYE CATALEPSY	SA	1.Challenge
11. POST-HYPNOTIC SUGGESTION	EF	3.Cognitive
12. HYPNOTIC AMNESIA	EF	3.Cognitive

Note: S: simulation; SA: simulation-adaptation; EF: executive function.

Finally, an important question regarding the HGSHS is whether the outcome of one category of suggestions predicts the outcomes of other categories. Based on SATH, the simulation-adaptation category encompasses items that require a combination of essential underlying mechanisms (i.e., cognitive-simulation and sensory-adaptation) necessary to comply with suggestions. Consequently, the outcome of simulation-adaptation suggestions might predict success in the simulation category and, to a lesser extent, also in the executive function category.

Together, in the current study, for solving several issues related to EFA, we used CFA and SEM to investigate the structural construct of HGSHS-A scores. Since CFA needs a theory, from which relevant hypotheses can be derived, after scrutinizing possible candidates, we chose the SATH and used it as the basis for our CFA and SEM. Based on this theory, a bifactor model was postulated, consisting of three specific grouping factors and a G-factor measured by all items. Further, the internal construct of grouping factors was investigated to establish a causal pathway between categories of suggestions.

2. Methods

2.1. Participants

A sample of 477 participants ($Mean\ age\ =\ 28.7\ years, SD\ =\ 12.6\ years$) was recruited. Several different methods have been used for finding prospective participants; besides inviting local Psychology students, the study was advertised on eBay Kleinanzeigen (https://www.ebay-kleinanzeigen.de) and local radio stations. The study had been approved by the ethics committee of the Institut für Psychologie of the Humboldt-Universität zu Berlin. Prior to the experiment, signed consents were obtained. Participation was compensated by free assessment of hypnotic-suggestibility or course credits.

Based on the most conservative estimation, the sample size of a CFA should be $N = 20 * free\ parameters$ (Tanaka, 1987). In our study, the number of free parameters in the basic model was 24, which shows our sample was big enough, $N \approx 20 * 24$. Further, based on $1 - \beta > 0.9$, $H0 < 0.05$, and $H1 > 0.1$ (Cohen, 2016), we calculated the required sample size for Root Mean Square Error of Approximation (RMSEA) (Preacher & Coffman, 2006), which yielded a minimum required sample size of, $N = 120$, which again confirms that the analyses conducted here have sufficient power to test presented hypotheses.

2.2. Measurements and Procedure

The HGSHS-A (Shor & Orne, 1962) has 12 suggestions (Table 1) and is designed for administration in group sessions. In the present study, we screened groups of 2-15 volunteers per session. At the beginning of the session, a short description of hypnosis and hypnotizability was given by a certified hypnotizer (A.Z.), as advised in the HGSHS-A manual (Shor & Orne, 1962). Afterward, a recorded German version of HGSHS-A (Bongartz, 1985) was administered while participants were required to follow the suggestions. After the presentation of all suggestions, participants completed a questionnaire regarding their experience, consisting of two sections. (1) An objective section inquired whether the participant had complied with each of the suggestions, and (2) a subjective section asked how strongly they had experienced the effect of each suggestion. In the objective section, compliance or non-compliance was scored as 1 or 0, respectively, for the first 11 suggestions; the 12th suggestion (i.e., hypnotic amnesia) was scored as 0, if less than 4 items could be remembered, and otherwise as 1. Hence, participants could receive a total score of $0 =< hypnotic\ suggestibility\ =< 12$.

2.3. Data analyses

All data analyses were conducted in R (R Core Team, 2013); for CFA and SEM, the lavaan package was used (Rosseel, 2012). As the objective scores of HGSHS-A are binary, the diagonally weighted least squares (DWLS) was used to estimate model parameters, and the full weight matrix (WLSMV) was utilized to compute robust standard errors and mean- and variance-adjusted test statistics. Since the study benefitted from a large sample, WLSMV was preferred for ordinal data in comparison to maximum likelihood (ML) or robust maximum likelihood (MLR) (Li, 2016). Distributions were fitted with VGAM (Yee, 2010; Yee, 2015) and fitdistrplus (Delignette-Muller & Dutang, 2015).

3. Results and Discussion

3.1. Descriptive results

Figure 2 presents the distribution of HGSHS-A scores; since these parameters are ordinal, they cannot be expected to have a normal distribution. However, the methods used for both CFA and SEM analyses and calculation of estimated loadings in CFA and SEM are robust and insensitive to deviations from normality. Regarding the distribution of HGSHS-A scores, three points should be noted. First, the scores show a beta-binomial distribution with estimated $\mu =$

0.52 and $\rho = 0.099$ [1] (the distribution fit indices are presented in Table 4). Second, it could be argued, as in our study, participants were volunteers, the sampling procedure might have been biased toward more hypnotic-suggestible participants. However, the distribution is not biased (skewed) toward low- or high-hypnotic-suggestibles. Third, the bimodal shape of the distribution is of great interest and will be discussed in section 3.4.

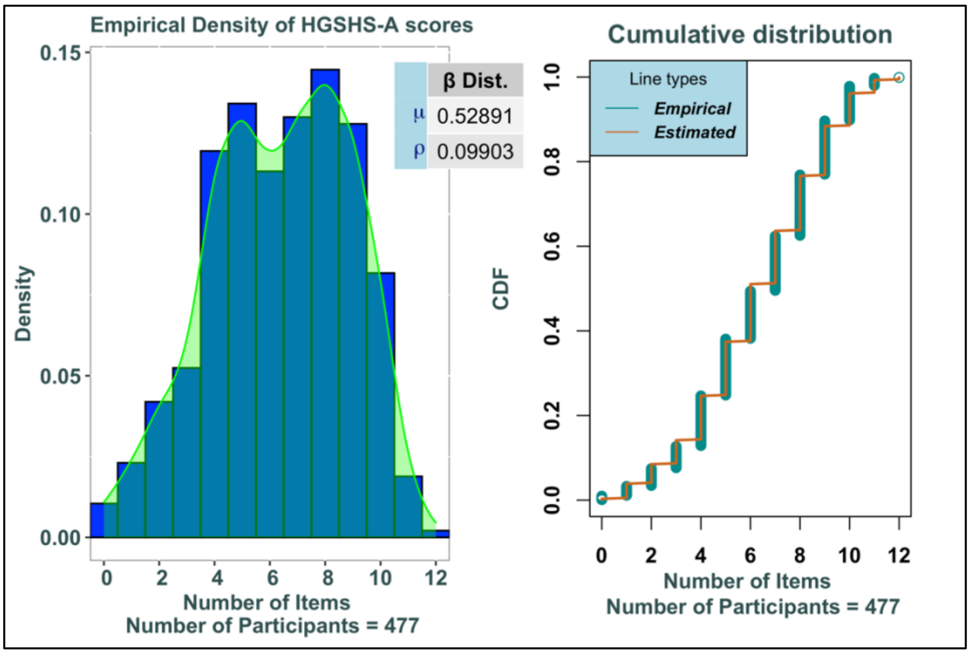


Figure 2. Left: Histogram and density estimation distribution of HGSHS-A scores. Right: Cumulative distribution of HGSHS-A scores.

3.2. Confirmatory Factor Analyses

For testing the hypotheses outlined in section 1.1, we fitted four models to the data (Fig. 3). First, we tested a single-factor model, with the hypothesis that there might be a single G-factor, which can account for all the variance in the data. Model 2 (i.e., the three-factor model) represents

---

[1] More familiar indices of beta binomial distribution can be calculated by $\alpha = \mu(1-\rho)/\rho$ and $\beta = (1-\mu)(1-\rho)/\rho$.

the basic multifactor model introduced in Table 1, where each suggestion is related to only one of the three grouping factors.

Models 3 and 4 represent two bifactor models that were proposed in section 1.1. to enhance the basic multifactor model. In conventional bifactor models, it is necessary to assume orthogonality between latent factors. That is, the correlation between latent factors are constrained to zero (Reise, 2012). Otherwise, interpretation may be complicated (Musek, 2017; Reise, 2012), and models may be unidentifiable (i.e., common anomalies of bifactor models) (Eid, Geiser, Koch, & Heene, 2017; Eid et al., 2018). Anomalies in conventional bifactor models may arise if data were not obtained in a two-level sampling procedure (Eid et al., 2017); that is, if not both, participants, as well as items to participants, have been randomly assigned. Such a two-level sampling is not possible for HGSHS-A since items are fixed. Therefore, based on the suggestions of Eid et al. (2017), we computed bifactor- $(S-1)$ and bifactor- $(S.I-1)$ models instead of conventional bifactor models. In the bifactor- $(S-1)$ model (Model 3), one of the grouping factors, the simulation factor, was conceptualized as a G-factor measured by all HGSHS-A items. The reason for choosing the simulation factor as the reference domain was that cognitive-simulation is a top-down process required for responding to different forms of suggestions. Sensory-adaptation and executive functions, in contrast, are necessary only for a special group of suggestions. In the bifactor- $(S.I-1)$ model (Model 4), in addition to three *correlated grouping factors*, a G-factor measured by all HGSHS-A items was assumed. In this model, one item is reserved only for the G-factor. This indicator serves to distinguish the G-factor from the grouping factors. Item 3 of HGSHS-A (Hand Lowering) was chosen as the reference indicator since it is a simple suggestion that arguably relates more to psychosocial variables than any top-down cognitive processes.

Table 2. Fit Indices for the Full Confirmatory Factor Analysis Model and Reduced Models

Model	*df*	χ^2 [a]	RMSEA [90% CI] [b]	SPMR [c]	CFI [d]	TLI [d]
G-factor model	54	142.6 ***	0.059 [0.047-0.079]	0.105	0.934	0.919
Three-factor model	51	80.5 **	0.035 [0.019-0.049]	0.079	0.978	0.972
Bifactor- $(S-1)$ model	45	61.2	0.028 [0.000-0.044]	0.068	0.988	0.982
Bifactor- $(S.I-1)$ model	**40**	**33.7**	**0.000 [0.000-0.024]**	**0.048**	**1**	**1.008**

Note: The endorsed model is indicated in bold. SPMR: standardized root-mean-squared residual; RMSEA: Root Mean Square Error of Approximation; CFI: Bentler's Comparative Fit Index; TLI: Tucker-Lewis Index.
[a] When χ^2 test is not significant the model fits the data. However, as the $N = 477$ was very large, it is expected that H_0 would be over-rejected.
[b] Lower values of RMSEA indicate better fit, with values < .05 indicating a close fit to the data (Xia & Yang, 2019). For $1-\beta > 0.9$, $H0 < 0.05$, and $H1 > 0.1$ the required sample size is $N > 120$.
[c] Lower values of SRMR indicate better fit, with SRMR < .08 indicating a close fit to the data.
[d] Values > .95 for CFI and TLI indicate a good fit (Xia & Yang, 2019). TLI is not normalized and may have values > 1.
* $p < .05$; ** $p < .01$; *** $p < .001$

Table 2 summarizes the fit indices for all four models, graphically presented in Figure 3. Based on the results shown in Table 2, and considering adjusted thresholds, the G-factor model (Model 1) showed a poor fit to the data. The three-factor model fared better and had a lower standardized root-mean-squared residual (RMSEA) compared to Model 1; however, it still showed only a modest fit. In contrast, both the bifactor- $(S-1)$ (# 3) and bifactor- $(S.I-1)$ models (# 4) showed exact fits to the data. The bifactor- $(S.I-1)$ model has the lowest χ^2, and standardized root mean squared residual (SPMR), indicating a better fit in comparison to other models, which is expected, as more complex models usually fit the data better.

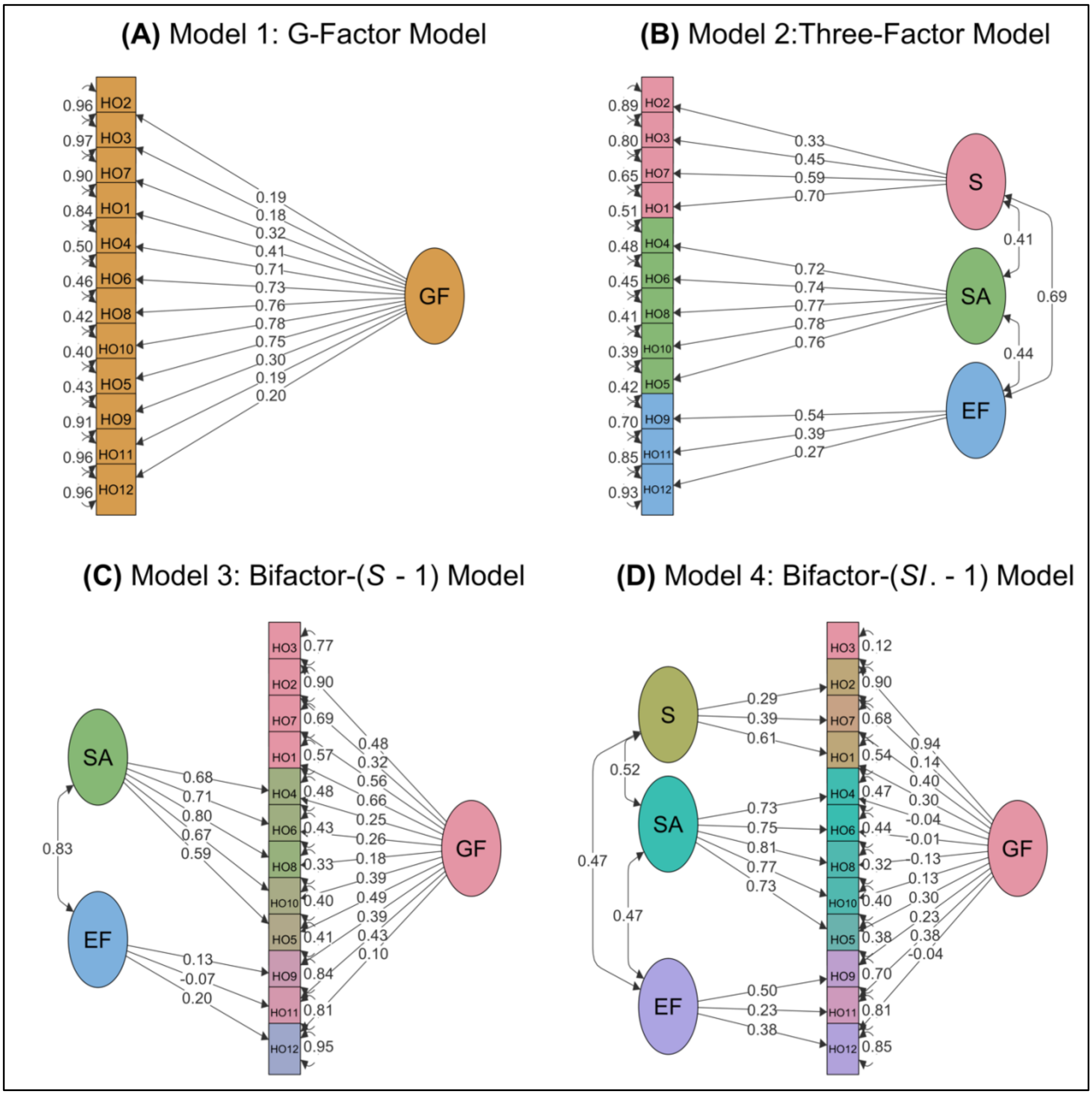


Figure 3. Estimated loadings of the CFA models. (A) G-factor model, (B) three-factor model, (C) bifactor- $(S-1)$ model, and (D) bifactor- $(S.I-1)$ model. On the single-headed arrows, standardized factor loadings are given. All loadings in the G-factor and three-factor models are significant, $p < .05$. In the bifactor- $(S-1)$ model, the loadings of EF factors and HO12 on GF are not significant; however, other loadings are significant, $p < .05$. In the bifactor- $(SI.-1)$ model, the loadings of HO2, HO4, HO6, HO8, HO10, and HO12 on the G-factor are not significant; however, other loadings are significant, $p < .05$. Loadings are equivalent to standardized regression coefficients (beta weights), and they are estimated with diagonally weighted least squares. The self-loops show error terms. Squaring these terms gives an estimate of the variance for each task that is not accounted for by the latent construct. The curved, double-

headed arrows indicating correlation coefficients between latent variables, all of which, except the correlation between EF and S in bifactor- $(S-1)$ model, are significant, $p < .05$.
Note: S: simulation; SA: simulation-adaptation; EF: executive function.

Even though only the bifactor- $(S-1)$ and bifactor- $(SI.-1)$ models closely fit the data, we compared all four models using the likelihood ratio test (Tab. 3). We reasoned that, since we had a large number of participants, χ^2 might over-reject null hypotheses (*H0*: a given model does not fit the data). All of our models can be tested using the likelihood ratio test, as suggested by Reise (2012). The likelihood ratio tests were conducted hierarchically; that is, a model was only compared to the next simpler model. The results of these tests (Table 3) confirm that the G-factor model (Model 1) is least capable of capturing the variance in the data. Hence, the HGSHS-A is definitely not a homogenous scale as it was initially assumed. Second, the bifactor- $(S-1)$ model (Model 3) fits the data significantly better compared to the three-factor model, corroborating our theoretically derived hypothesis that cognitive-simulation is the shared top-down cognitive process employed in all forms of suggestions. Finally, the bifactor- $(S.I-1)$ model (Model 4) is significantly better in comparison to the bifactor- $(S-1)$ model, supporting our hypothesis that hypnotizability and suggestibility can be distinguished.

Table 3. Results of likelihood ratio tests comparing the four models

Competing models		*df*	$\chi^{2\,a}$
Three-factor model	G-factor model	3	47.9 ***
Bifactor- $(S-1)$	Three-factor model	6	18.9 **
Bifactor- $(S.I-1)$	Bifactor- $(S-1)$	5	22.2 ***

Note: [a] If the χ^2 test is significant the more complex model will be endorsed, if not, the simpler model is endorsed.
** $p < .01$; *** $p < .001$

With regard to the bifactor- $(S.I\ -1)$ model, one should consider that a model with three correlated first-order factors without a G-factor is equivalent to a second-order G-factor model; that is, a model in which, besides three specific uncorrelated factors, a second-order G-factor is assumed (Eid et al., 2017). Hence, in our bifactor- $(S.I\ -1)$ model, two G-factors, one hidden and one explicit, are assumed, which capture variance from two different sources. In the introduction, we argued that based on a proposal by Kirsch (1997), which is also incorporated in SATH (Zahedi & Sommer, 2021), hypnotic-suggestibility, as measured by HGSHS-A, can be decomposed into suggestibilities (capability of responding to different types of suggestions in general) and hypnotizability (the increase in suggestibilities due to the hypnotic condition). Consequently, in our bifactor- $(S.I\ -1)$ model, the correlated grouping factors measure suggestibilities, and the G-factor measures hypnotizability. Although suggestibility and its components can be clearly defined by SATH, hypnotizability is less identifiable and can be related to various psychosocial variables, including willingness and openness (Green & Lynn, 2011; Lynn, Laurence, & Kirsch, 2015), the prior expectations about hypnosis (Kirsch & Lynn, 1997; Terhune, Cleeremans, Raz, & Lynn, 2017), expectations induced by the wordings of suggestions (Lynn, Neufeld, & Matyi, 1987; Matthews, Bennett, Bean, & Gallagher, 1985; Spanos, 1971), rapport with the hypnotist (Lynn et al., 2019), and motivation to respond to suggestions (Jones & Spanos, 1982).

Two critical points related to the loadings in the bifactor- $(S\ -\ 1)$ and $(SI.-1)$ models should be discussed here. Firstly, in the bifactor- $(S\ -\ 1)$ model, executive function indicators loaded significantly on the G-factor but not on the executive function factor. This result could be predicted as in section 1.1., we argued that for executive function suggestions, participants need first to find appropriate mental imagery, and then these suggestions turn into typical simulation or simulation-adaptation suggestions. As each of these suggestions poses a unique problem, it seems that cognitive-simulation (the G-factor) is more salient than problem-solving (the executive function factor) in responding to these suggestions. Secondly, in the bifactor- $(SI.-1)$ model (Model 4), simulation-adaptation indicators loaded strongly on the simulation-adaption factor but very weakly on the G-factor, indicating that participants responded to simulation-adaptation suggestions less than expected considering their motivations and expectations. This result could also be anticipated as simulation-adaption suggestions require two essential top-down cognitive processes, which makes motivations, expectations, and other psychosocial variables less relevant or irrelevant in responding to them.

3.3. Structural Equation Modeling

Next, we tested our hypotheses that the specific grouping factor, which is parceling the suggestions with all the essential top-down processes required for different suggestibilities, can predict the outcome of the other grouping factors. In other words, we expected that the simulation-adaptation factor can predict the simulation and executive function factors, but not vice versa. We tested this hypothesis in the models with three grouping factors (Models 2 and 4; Fig. 4). Both the executive function factor, as well as the simulation factor, regressed significantly to the simulation-adaption factor, $Ps < .05$, but in none of these models, did simulation-adaptation regress significantly to executive function and simulation factors, $Ps > .1$. Further, in the bifactor- $(SI.-1)$ model, the correlation between the executive-function and simulation factors became insignificant when they regressed to the simulation-adaption factor, indicating that relationships between these factors can be reduced to regression of the executive function and simulation factors on the simulation-adaption factor.

These results corroborate SATH's claim that simulation-adaptation suggestions encompass the essential components of suggestibility. In other words, simulation-adaptation suggestions need a balanced interaction between vital top-down cognitive processes employed for responding to different forms of suggestions. That is, imagination (i.e., cognitive-simulation) and top-down downregulation of sensory information (i.e., sensory-adaption) are both required for responding to simulation-adaptation suggestions, distinguishing them from other forms of suggestions. This conclusion has a notable implication for using standardized scales of hypnotic susceptibility in clinical and experimental usage, as will be discussed below.

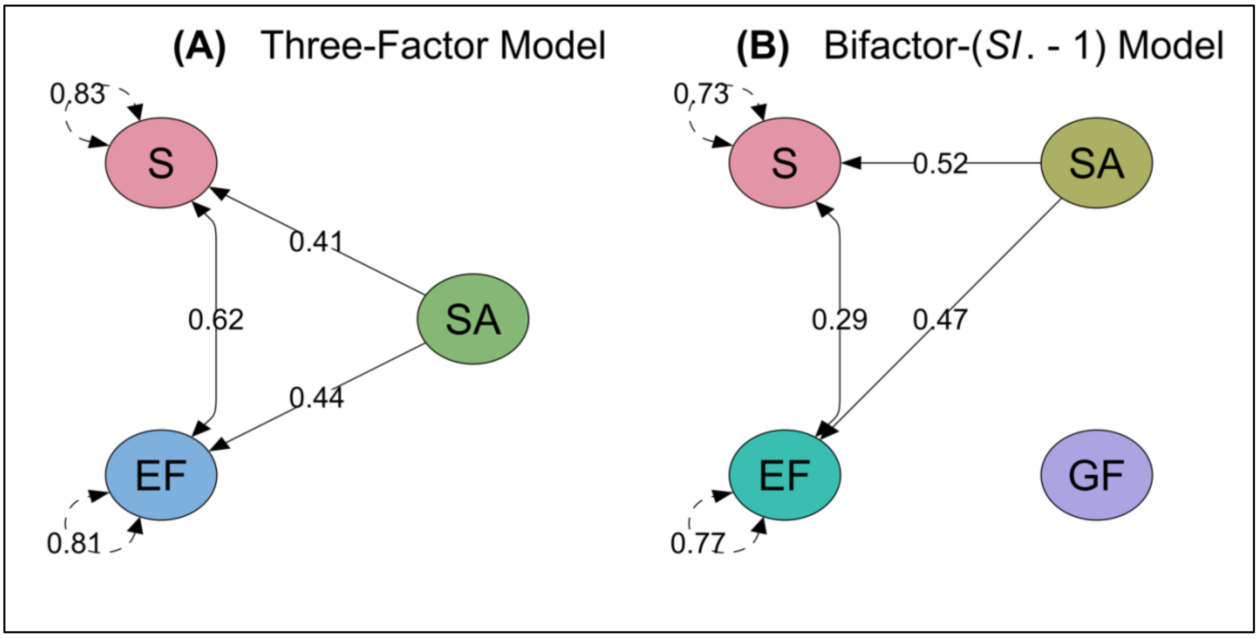


Figure 4. The structural segment of (A) the three-factor, and (B) bifactor- $(SI. - 1)$ models. All correlation and regression coefficients, except the correlation between $EF \sim\sim S$ in the bifactor-$(SI. - 1)$ model, are significant, $p < .05$.

Note: Adding regressions did not change the models, as previously we had assumed correlations between factors. Therefore, we only presented the structural segments of the models.

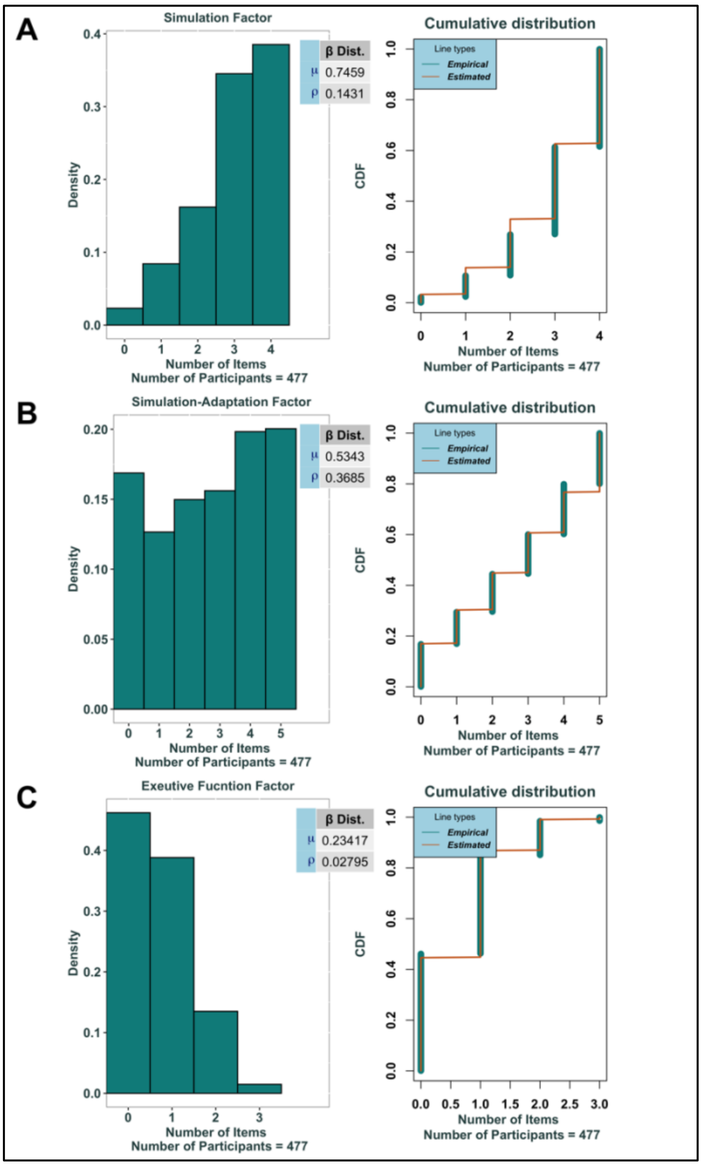


Figure 5. Distributions of the (A) Simulation, (B) Simulation-Adaptation, and (C) Executive Function factor scores. Left: Histograms of distributions. Right: Cumulative distributions of the empirical and estimated data, based on a beta-binomial distribution by the given μ and ρ.

Figure 5 shows the distributions of factors' scores (for details, see Table 1). As shown in Table 4, all three distributions are beta-binomial. However, only the simulation-adaptation factor showed estimated $\alpha < 1$ and $\beta < 1$, indicating a U-shape distribution. By considering the structure of grouping factors, the fit of the proposed models, and the distribution of factors' scores, we can finally discuss the observed bimodal distribution of HGSHS-A scores (see Fig. 1). Importantly, this bimodality was also observed in many other studies (for review, see Balthazard & Woody, 1989). Three possible explanations may be offered for this distribution. (1) The bimodality in HGSHS-A total scores may be the consequence of overdispersion of a beta-binomial distribution. In other words, the bimodality may be caused by smearing of the peak of the distribution and can be considered as noise. (2) If we consider that the simulation-adaptation factor has a U-shaped beta-binomial distribution and that the simulation-adaptation factor predicts both executive function and simulation factors, we may also suggest that the bimodality in HGSHS-A is forced by the simulation-adaptation distribution. Therefore, hypnotic-suggestibility may be related to a trait with a U-shape distribution in the population, and assuming a normal distribution does not represent this facet. In other words, there is a higher chance that a person would be either fully capable or entirely incapable of responding to simulation-adaption suggestions rather than in between. Based on the discussion regarding the processes involved in simulation-adaptation suggestions, one may conclude that in a given participant, the interaction between cognitive-simulation (i.e., factor S) and sensory-adaptation (i.e., factor SA) either succeeds in making imaginations dominant over sensory inputs, rendering this participant high-hypnotic-suggestible, or otherwise the participant will be low-hypnotic-suggestible. Importantly, this conclusion does not mean that all hypnotic-suggestible participants are the same. That is, a given participant might have a powerful imagination (i.e., cognitive-simulation) and therefore needs less sensory-adaptation (i.e., top-down downregulation of sensory input), and another might be very talented in sensory-adaptation, and hence, is less dependent on imagination (e.g., Terhune, Cardena, & Lindgren, 2011).

Finally, (3) the observed bimodality might be due to the superimposition of two unimodal distributions. Especially, given that the bifactor- $(SI.-1)$ model was the best fit for the data, one may assume that hypnotizability is related to two underlying mechanisms, namely, suggestibility and hypnotizability, both of which have a normal distribution in the general population. However, as they might have positive versus negative skewness, when they are added together under the general concept of hypnotic-susceptibility, they may cause HGSHS-A scores to have a bimodal distribution. It must be noted that these interpretations need to be experimentally investigated before one can draw any firm conclusion.

Table 4. Fit indices for the distributions of the HGSHS-A scores and grouping factors

Distribution	Fitted Distribution	ΔAIC [a]	ΔBIC [a]	Estimated α and β
HGSHS-A scores	**Beta-Binomial**	**0**	**0**	**4.81 - 4.28**
	Poisson	45	42	-
	Negative Binomial	47	48	-
SA scores	**Beta-Binomial**	**0**	**0**	**.99 - .79**
	Poisson	204	200	-
	Negative Binomial	199	199	-
S scores	**Beta-Binomial**	**0**	**0**	**4.46 – 1.52**
	Poisson	328	324	-
	Negative Binomial	326	330	-
EF scores	**Beta-Binomial**	**0**	**0**	**8.14 – 26.63**
	Poisson	11	7	-
	Negative Binomial	13	13	-

Note: The endorsed distribution is highlighted in bold.
S: simulation; SA: simulation-adaptation; EF: executive function.
[a] When $\Delta AIC > 10$, the model with minimum AIC will be endorsed (Burnham & Anderson, 2016). $\Delta AIC = AIC_i - AIC_{minimum}$, and $\Delta BIC = BIC_i - BIC_{minimum}$. The AIC are corrected for the finite sampling (AIC_c).
* $p < .05$; ** $p < .01$; *** $p < .001$

4. General Discussion

Our results attest to the advantages of CFA and SEM over EFA. First, since CFA is theory-driven, the results can be interpreted with greater confidence and are not subjected to post hoc interpretations. For instance, the bifactor- $(SI.-1)$ model consists of two parts, a G-factor and the basic three-factor model. Regarding the basic three-factor part, there is an exact correspondence between the theory-driven basic three-factor model and the dominant solution of previous EFAs (e.g., McConkey et al., 1980) (see Tab. 1). However, in previous EFA (e.g., McConkey et al., 1980; Oakman & Woody, 1996; Piesbergen & Peter, 2006), grouping factors and their indicators were data-driven and explained post hoc, distinguishing them from theory-driven (a priori) hypotheses needed for CFA. This issue hindered previous EFAs in agreeing on the most relevant model since several statistically-indistinguishable models fitted the data similarly well. In the current study, on the other hand, the latent factors and their indicators were derived from SATH (Zahedi & Sommer, 2021), and therefore, the uncertainty about the number and nature of latent factors were minimized.

Second, even though multiple studies showed that HGSHS scores are best explained by more than one latent factor (McConkey et al., 1980; Woody et al., 2005), to the best of our knowledge, no previous study has applied bifactor modeling to data from HGSHS or any other standardized hypnotic susceptibility scale. However, bifactor modeling is of great relevance for analyzing hypnotic-suggestibility according to the proposition of Kirsch (1997) and SATH. In these accounts, standardized scales such as the SSHS or HGSHS measure hypnotic-suggestibility, consisting of two components, namely, suggestibility and hypnotizability. Our results show that adding a G-factor, measuring the common variance of all items of the HGSHS, to the basic multifactor model significantly enhanced model fit. This G-factor possibly measures global hypnotizability. Hence, the current results corroborate the idea that in addition to the specific grouping factors, tapping into different suggestibilities, a G-factor, measuring hypnotizability is necessary to fully explain the variance of HGSHS scores.

Third, previous studies (McConkey et al., 1980; Woody et al., 2005) have demonstrated multiple hypnotic-suggestibilities but did not investigate the relations or pathways between these latent factors. Our SEM results showed that the outcome of the simulation-adaptation factor, which requires a combination of the two critical top-down processes involved in suggestibility, can predict the outcomes of both the simulation and executive function factors but not vice versa.

Our results regarding the causal pathways have notable implications for the future applications of standardized tests in clinical and experimental settings. Usually, hypnotic suggestions in clinical situations benefit from several properties that are not covered by the HGSHS. (1) In clinical applications, there is a cohesive story connecting different suggestions. (2) Clinical suggestions present perspicuous and elaborate strategies, and (3) involve a flexible procedure that can be adapted to client's preferred speed. Because of these differences with clinical applications, the HGSHS is not an optimal or even useful predictor of suggestibility outside of screening sessions. This fact is reflected in the problems of standardized hypnotic-suggestibility scales in predicting outcomes of hypnotherapy (e.g., Alladin & Alibhai, 2007; Golden, 2012; Schoenberger, 2000), interventions for pain reduction (e.g., Perri, Rossani, & Di Russo, 2019) or interventions targeting modification of food preferences (e.g., Zahedi, Luczak, et al., 2020). A suitable hypnotic-suggestibility scale for clinical purposes might focus on simulation-adaptation suggestions as (a) these suggestions measure the interaction between cognitive-simulation (i.e., imagination) and sensory-adaptation (i.e., top-down driven downregulation of sensory input), which are the essential elements of suggestibility. (b) In contrast to executive function suggestions, sensory-adaptation suggestions are appropriately elaborated and present a clear strategy. Hence, they do not rely on participants' problem-solving capabilities to compensate for vague suggestions. (c) In contrast to simulation suggestions, sensory-adaptation suggestions require more than only subjective re-coding of a phenomenon. Therefore, these suggestions should be closer to what participants usually experience outside of screening sessions and better for predicting hypnotic-suggestibility in applied settings.

With regard to experimental applications, standardized hypnotic-suggestibility scales might also not be as useful as deemed. Basic research in hypnosis frequently poses two types of questions. (1) How is hypnotic-suggestibility as a trait related to other traits and/or cognitive functions? This type of experimental research, designated intrinsic (Cox & Bryant, 2008; Wagstaff, 1996), asks, for example, whether hypnotic-suggestibility is related to the capability of concentration, fantasy, or daydreaming (for review, see Lynn et al., 2019). (2) Do (posy)hypnotic suggestions affect perception or performance in specific tasks, such as those measuring cognitive functions (for review, see Kihlstrom, 2013; Kihlstrom, 2014)? Such studies, sometimes referred to as instrumental (Cox & Bryant, 2008; Wagstaff, 1996), ask, for instance, whether (post)hypnotic suggestions can subdue pain perception (e.g., Perri et al., 2019) or facilitate inhibition of irrelevant but intrusive information (e.g., Zahedi et al., 2019).

When questions regarding the influence of hypnosis on any dependent variable are addressed, it is a common practice to use standardized hypnotic-suggestibility scales to categorize participants as low- versus high-hypnotic-suggestibles (for review, see Lifshitz, Aubert Bonn, Fischer, Kashem, & Raz, 2013). Then, for curbing the effects of confounding variables, low- and high-hypnotic-suggestibles are compared, effectively using the former group as controls for the latter (Cox & Bryant, 2008; Wagstaff, 1996). Jensen et al. (2017) discussed why the utilization of low-hypnotic-suggestibles as the only constituent of control groups might be misleading. Our results support the caveats of Jensen et al. (2017) concerning current screening tools. The variance in hypnotic-suggestibility scores appears to originate from two sources, differences in suggestibility and hypnotizability. Differences in suggestibility are caused by individual differences in the employment of several top-down processes and their interaction, including cognitive-simulation, sensory-adaptation, and problem-solving (Zahedi & Sommer, 2021). Further, differences in hypnotizability are likely influenced by multiple psychosocial factors, which are already discussed in section 3.2. Confirmatory Factor Analyses. Consequently, low-hypnotic-suggestible participants are distinguishable from high-hypnotic-suggestibles due to a combination of cognitive and psychosocial factors. Due to this uncertainty, the utilization of low- hypnotic-suggestibles as controls violates the basic assumption of a control condition. That is, participants in the control and experimental conditions must be identical in possible aspect except for one measurable property. When this assumption does not hold, no conclusion can be drawn from observed differences between the control and experimental groups. Noticeably, the HGSHS is not a homogenous instrument as a single G-factor model cannot reasonably fit the data, which underscores our concerns that a given HGSHS total score is appropriate for predicting participants' responses to an experimental suggestion.

For intrinsic hypnosis studies, employing available standardized suggestibility scales may be misleading, too. For instance, let's consider the inconsistent relationship between hypnotic-suggestibility and cognitive control. Several well-conducted studies using both psychometric and neural measures have recently shown that without hypnosis, high-hypnotic-suggestibles performed better than low-hypnotic-suggestibles in cognitive tasks (Kirenskaya, Storozheva, Solntseva, Novototsky-Vlasov, & Gordeev, 2019; Srzich et al., 2019). In contrast, Khodaverdi-Khani and Laurence (2016) observed inferior digit span performance in high-hypnotic-suggestibles compared to low-hypnotic-suggestibles, but there was no significant difference in an N-back task, revealing inconclusive findings with regard to WM performance. Furthermore, in a large sample ($N = 180$), Dienes et al. (2009) found no correlation between hypnotic-suggestibility and cognitive capabilities. The present study indicates why the findings of studies investigating the relation between hypnotic-suggestibility and cognitive control are inconclusive (Parris, 2017; Terhune et al., 2017). Studies investigating the relation between hypnotizability and other processes must take into account the bifactorial nature of the scales employed. Hypnotic-suggestibility scales involve two sources of variance, suggestibility and hypnotizability, which should be considered separately. Our concerns about current scales of hypnotic-suggestibility are shared by many other researchers in the field of hypnosis, questioning the applicability and usefulness of existing scales (Acunzo & Terhune, 2021; Jensen et al., 2017).

Several limitations of our study must be discussed. First, non-significant loadings on some factors are a common anomaly in bifactor modeling (Eid et al., 2017). We also observed this issue in a conventional bifactor model of HGSHS scores (see supplementary materials). Therefore, based on the suggestions of Eid et al. (2018) and Eid et al. (2017), we used the bifactor- ($S - 1$) and ($SI. -1$) models instead of the conventional bifactor model. Even though the anomalies were better controlled in these models, some of the indicators still had nonsignificant loadings (see Fig. 3). Even though these anomalies were interpreted post hoc (see section 3.2. Confirmatory Factor Analyses), they were not expected at the time of postulating these models. However, these anomalies do not call into question our interpretations or conclusions regarding our theory-driven hypotheses.

Further, in our study, we only employed the HGSHS for modeling hypnotic-suggestibility scores. In future studies, however, it will be beneficial to measure other top-down cognitive functions, such as top-down sensory-adaptation and cognitive-simulation, postulated by SATH to be important in responding to suggestions. However, one should notice that for measuring some of these top-down cognitive functions, such as sensory-adaptation, there is no standardized test available, and therefore, novel instruments have to be developed first.

In conclusion, in the current study, we conducted a CFA of HGSHS-A based on SATH (Zahedi & Sommer, 2021). Going beyond the results of previous EFAs (e.g., McConkey et al., 1980; Woody et al., 2005), our results showed that (1) the HGSHS-A is best explained by a bifactor model, in which a G-factor tapping into hypnotizability is assumed beside three specific grouping factors measuring different components of suggestibility, namely, simulation, simulation-adaptation, and executive function factors. (2) SEM of causal pathways between latent factors revealed that the outcome of simulation-adaptation suggestions, which require a combination of cognitive-simulation and sensory-adaptation, can predict the outcome of other suggestions. this finding corroborates SATH's claim that these two top-down processes are the essential elements of suggestibility. (3) Finally, our results have several important implications for future applications of the existing standardized scales of hypnotic susceptibility. First, in line with the conclusions of Acunzo and Terhune (2021), the current study shows the need for developing a new scale of hypnotic-suggestibility focused on simulation-adaptation suggestions for clinical and experimental applications. Second, in line with the proposition of Jensen et al. (2017), the current results show the importance of using control groups consisting of participants with similar rather than different hypnotic-suggestibility scores to experimental groups, and a desideratum for revisiting applications of standardized scales in studies investigating the relation between hypnotizability and other mental processes.

References

Acunzo, D., & Terhune, D. (2021). A critical review of standardized measures of hypnotic suggestibility. *International Journal of Clinical and Experimental Hypnosis*.

Adams, R. A., Shipp, S., & Friston, K. J. (2013). Predictions not commands: active inference in the motor system. *Brain Struct Funct, 218*(3), 611-643. doi:10.1007/s00429-012-0475-5

Alladin, A., & Alibhai, A. (2007). Cognitive hypnotherapy for depression: an empirical investigation. *International Journal of Clinical and Experimental Hypnosis, 55*(2), 147-166. doi:10.1080/00207140601177897

Balthazard, C. G., & Woody, E. Z. (1989). Bimodality, dimensionality, and the notion of hypnotic types. *International Journal of Clinical and Experimental Hypnosis, 37*(1), 70-89. doi:10.1080/00207148908410534

Bongartz, W. (1985). German norms for the Harvard Group Scale of Hypnotic Susceptibility, Form A. *International Journal of Clinical and Experimental Hypnosis, 33*(2), 131-139. doi:10.1080/00207148508406643

Braffman, W., & Kirsch, I. (1999). Imaginative suggestibility and hypnotizability: an empirical analysis. *Journal of Personality and Social Psychology, 77*(3), 578-587. doi:10.1037//0022-3514.77.3.578

Brown, H., Adams, R. A., Parees, I., Edwards, M., & Friston, K. (2013). Active inference, sensory attenuation and illusions. *Cognitive Processing, 14*(4), 411-427. doi:10.1007/s10339-013-0571-3

Brown, R. J., & Oakley, D. A. (2004). An integrative cognitive theory of hypnosis and high hypnotizability. *The highly hypnotizable person: Theoretical, experimental and clinical issues*, 152-186.

Burnham, K. P., & Anderson, D. R. (2016). Multimodel Inference. *Sociological Methods & Research, 33*(2), 261-304. doi:10.1177/0049124104268644

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences, 36*(3), 181-204. doi:10.1017/S0140525X12000477

Cohen, J. (2016). Statistical Power Analysis. *Current Directions in Psychological Science, 1*(3), 98-101. doi:10.1111/1467-8721.ep10768783

Cojan, Y., Archimi, A., Cheseaux, N., Waber, L., & Vuilleumier, P. (2013). Time-course of motor inhibition during hypnotic paralysis: EEG topographical and source analysis. *Cortex, 49*(2), 423-436. doi:10.1016/j.cortex.2012.09.013

Cojan, Y., Waber, L., Schwartz, S., Rossier, L., Forster, A., & Vuilleumier, P. (2009). The brain under self-control: modulation of inhibitory and monitoring cortical networks during hypnotic paralysis. *Neuron, 62*(6), 862-875. doi:10.1016/j.neuron.2009.05.021

Cooper, S. R., Jackson, J. J., Barch, D. M., & Braver, T. S. (2019). Neuroimaging of individual differences: A latent variable modeling perspective. *Neuroscience and Biobehavioral Reviews, 98*, 29-46. doi:10.1016/j.neubiorev.2018.12.022

Coulacoglou, C., & Saklofske, D. H. (2017). Advances in Latent Variable Measurement Modeling. In *Psychometrics and Psychological Assessment* (pp. 67-88).

Cox, R. E., & Bryant, R. A. (2008). Advances in hypnosis research: methods, designs and contributions of intrinsic and instrumental hypnosis. *The Oxford handbook of hypnosis: Theory, research, and practice, 2008*, 311-336.

Delignette-Muller, M. L., & Dutang, C. (2015). fitdistrplus: AnRPackage for Fitting Distributions. *Journal of Statistical Software, 64*(4). doi:10.18637/jss.v064.i04

Dienes, Z., Brown, E., Hutton, S., Kirsch, I., Mazzoni, G., & Wright, D. B. (2009). Hypnotic suggestibility, cognitive inhibition, and dissociation. *Consciousness and Cognition, 18*(4), 837-847. doi:10.1016/j.concog.2009.07.009

Dienes, Z., & Hutton, S. (2013). Understanding hypnosis metacognitively: rTMS applied to left DLPFC increases hypnotic suggestibility. *Cortex, 49*(2), 386-392. doi:10.1016/j.cortex.2012.07.009

Dienes, Z., & Perner, J. (2007). Executive control without conscious awareness: The cold control theory of hypnosis. *Hypnosis and conscious states: The cognitive neuroscience perspective*, 293-314.

Egner, T., & Raz, A. (2007). Cognitive control processes and hypnosis. *Hypnosis and conscious states: The cognitive neuroscience perspective*, 29-50.

Eid, M., Geiser, C., Koch, T., & Heene, M. (2017). Anomalous results in G-factor models: Explanations and alternatives. *Psychological Methods, 22*(3), 541-562. doi:10.1037/met0000083

Eid, M., Krumm, S., Koch, T., & Schulze, J. (2018). Bifactor Models for Predicting Criteria by General and Specific Factors: Problems of Nonidentifiability and Alternative Solutions. *J Intell, 6*(3). doi:10.3390/jintelligence6030042

Elkins, G. R., Barabasz, A. F., Council, J. R., & Spiegel, D. (2015). Advancing research and practice: The revised APA Division 30 definition of hypnosis. *American Journal of Clinical Hypnosis, 57*(4), 378-385. doi:10.1080/00029157.2015.1011465

Farah, M. J. (1988). Is visual imagery really visual? Overlooked evidence from neuropsychology. *Psychological Review, 95*(3), 307-317. doi:10.1037/0033-295x.95.3.307

Frank, T. D. (2016). Perception adapts via top-down regulation to task repetition: A Lotka-Volterra-Haken modeling analysis of experimental data. *Journal of Integrative Neuroscience, 15*(1), 67-79. doi:10.1142/S0219635216500059

Friston, K. (2010). The free-energy principle: a unified brain theory? *Nature Reviews: Neuroscience, 11*(2), 127-138. doi:10.1038/nrn2787

Galea, V., Woody, E. Z., Szechtman, H., & Pierrynowski, M. R. (2010). Motion in response to the hypnotic suggestion of arm rigidity: a window on underlying mechanisms. *International Journal of Clinical and Experimental Hypnosis, 58*(3), 251-268. doi:10.1080/00207141003760561

Golden, W. L. (2012). Cognitive hypnotherapy for anxiety disorders. *American Journal of Clinical Hypnosis, 54*(4), 263-274. doi:10.1080/00029157.2011.650333

Green, J. P., & Lynn, S. J. (2011). Hypnotic responsiveness: expectancy, attitudes, fantasy proneness, absorption, and gender. *International Journal of Clinical and Experimental Hypnosis, 59*(1), 103-121. doi:10.1080/00207144.2011.522914

Hammond, D. C. (1998). *Hypnotic induction and suggestion*. Chicago, IL: American Society of Clinical Hypnosis.

Harrington, D. (2009). *Confirmatory factor analysis*: Oxford university press.

Hesslow, G. (2002). Conscious thought as simulation of behaviour and perception. *Trends in Cognitive Sciences, 6*(6), 242-247. doi:10.1016/s1364-6613(02)01913-7

Iani, C., Ricci, F., Baroni, G., & Rubichi, S. (2009). Attention control and susceptibility to hypnosis. *Consciousness and Cognition, 18*(4), 856-863. doi:10.1016/j.concog.2009.07.002

Iani, C., Ricci, F., Gherri, E., & Rubichi, S. (2006). Hypnotic suggestion modulates cognitive conflict: the case of the flanker compatibility effect. *Psychological Science, 17*(8), 721-727. doi:10.1111/j.1467-9280.2006.01772.x

Jensen, M. P., Adachi, T., Tome-Pires, C., Lee, J., Osman, Z. J., & Miro, J. (2015). Mechanisms of hypnosis: toward the development of a biopsychosocial model. *International Journal of Clinical and Experimental Hypnosis, 63*(1), 34-75. doi:10.1080/00207144.2014.961875

Jensen, M. P., Jamieson, G. A., Lutz, A., Mazzoni, G., McGeown, W. J., Santarcangelo, E. L., . . . Terhune, D. B. (2017). New directions in hypnosis research: strategies for advancing the cognitive and clinical neuroscience of hypnosis. *Neurosci Conscious, 3*(1). doi:10.1093/nc/nix004

Jones, B., & Spanos, N. P. (1982). Suggestions for altered auditory sensitivity, the negative subject effect and hypnotic susceptibility: A signal detection analysis. *Journal of Personality and Social Psychology, 43*(3), 637-647. doi:10.1037/0022-3514.43.3.637

Khodaverdi-Khani, M., & Laurence, J.-R. (2016). Working memory and hypnotizability. *Psychology of Consciousness: Theory, Research, and Practice, 3*(1), 80-92. doi:10.1037/cns0000058

Kihlstrom, J. F. (2008). The domain of hypnosis, revisited. *The Oxford handbook of hypnosis: Theory, research and practice*, 21-52.

Kihlstrom, J. F. (2013). Neuro-hypnotism: prospects for hypnosis and neuroscience. *Cortex, 49*(2), 365-374. doi:10.1016/j.cortex.2012.05.016

Kihlstrom, J. F. (2014). Hypnosis and cognition. *Psychology of Consciousness: Theory, Research, and Practice, 1*(2), 139-152. doi:10.1037/cns0000014

Kirenskaya, A. V., Storozheva, Z. I., Solntseva, S. V., Novototsky-Vlasov, V. Y., & Gordeev, M. N. (2019). Auditory Evoked Potentials Evidence for Differences in Information Processing between High and Low Hypnotizable Subjects. *International Journal of Clinical and Experimental Hypnosis, 67*(1), 81-103. doi:10.1080/00207144.2019.1553764

Kirsch, I. (1997). Suggestibility or hypnosis: what do our scales really measure? *International Journal of Clinical and Experimental Hypnosis, 45*(3), 212-225. doi:10.1080/00207149708416124

Kirsch, I., & Lynn, S. J. (1997). Hypnotic involuntariness and the automaticity of everyday life. *American Journal of Clinical Hypnosis, 40*(1), 329-348. doi:10.1080/00029157.1997.10403402

Kirsch, I., & Lynn, S. J. (1998). Dissociation theories of hypnosis. *Psychological Bulletin, 123*(1), 100-115. doi:10.1037/0033-2909.123.1.100

Landry, M., Lifshitz, M., & Raz, A. (2017). Brain correlates of hypnosis: A systematic review and meta-analytic exploration. *Neuroscience and Biobehavioral Reviews, 81*(Pt A), 75-98. doi:10.1016/j.neubiorev.2017.02.020

Li, C. H. (2016). Confirmatory factor analysis with ordinal data: Comparing robust maximum likelihood and diagonally weighted least squares. *Behavior Research Methods, 48*(3), 936-949. doi:10.3758/s13428-015-0619-7

Lifshitz, M., Aubert Bonn, N., Fischer, A., Kashem, I. F., & Raz, A. (2013). Using suggestion to modulate automatic processes: from Stroop to McGurk and beyond. *Cortex, 49*(2), 463-473. doi:10.1016/j.cortex.2012.08.007

Lopresti-Goodman, S. M., Turvey, M. T., & Frank, T. D. (2013). Negative hysteresis in the behavioral dynamics of the affordance "graspable". *Atten Percept Psychophys, 75*(5), 1075-1091. doi:10.3758/s13414-013-0437-x

Ludwig, V. U., Seitz, J., Schonfeldt-Lecuona, C., Hose, A., Abler, B., Hole, G., . . . Walter, H. (2015). The neural correlates of movement intentions: A pilot study comparing hypnotic and simulated paralysis. *Consciousness and Cognition, 35*, 158-170. doi:10.1016/j.concog.2015.05.010

Lynn, S. J., & Green, J. P. (2011). The sociocognitive and dissociation theories of hypnosis: toward a rapprochement. *International Journal of Clinical and Experimental Hypnosis, 59*(3), 277-293. doi:10.1080/00207144.2011.570652

Lynn, S. J., Green, J. P., Polizzi, C. P., Ellenberg, S., Gautam, A., & Aksen, D. (2019). Hypnosis, hypnotic phenomena, and hypnotic responsiveness: Clinical and Research Foundations-A 40-Year Perspective. *International Journal of Clinical and Experimental Hypnosis, 67*(4), 475-511. doi:10.1080/00207144.2019.1649541

Lynn, S. J., Laurence, J. R., & Kirsch, I. (2015). Hypnosis, suggestion, and suggestibility: an integrative model. *American Journal of Clinical Hypnosis, 57*(3), 314-329. doi:10.1080/00029157.2014.976783

Lynn, S. J., Neufeld, V., & Matyi, C. L. (1987). Inductions versus suggestions: Effects of direct and indirect wording on hypnotic responding and experience. *Journal of Abnormal Psychology, 96*(1), 76-79. doi:10.1037/0021-843x.96.1.76

Lynn, S. J., Rhue, J. W., & Weekes, J. R. (1990). Hypnotic involuntariness: A social cognitive analysis. *Psychological Review, 97*(2), 169-184. doi:10.1037/0033-295x.97.2.169

Matthews, W. J., Bennett, H., Bean, W., & Gallagher, M. (1985). Indirect versus direct hypnotic suggestions--an initial investigation: a brief communication. *International Journal of Clinical and Experimental Hypnosis, 33*(3), 219-223. doi:10.1080/00207148508406650

Mazzoni, G., Rotriquenz, E., Carvalho, C., Vannucci, M., Roberts, K., & Kirsch, I. (2009). Suggested visual hallucinations in and out of hypnosis. *Consciousness and Cognition, 18*(2), 494-499. doi:10.1016/j.concog.2009.02.002

McConkey, K. M., Sheehan, P. W., & Law, H. G. (1980). Structural analysis of the Harvard Group Scale of Hypnotic Susceptibility, Form A. *International Journal of Clinical and Experimental Hypnosis, 28*(2), 164-175. doi:10.1080/00207148008409838

McGeown, W. J., Venneri, A., Kirsch, I., Nocetti, L., Roberts, K., Foan, L., & Mazzoni, G. (2012). Suggested visual hallucination without hypnosis enhances activity in visual areas of the brain. *Consciousness and Cognition, 21*(1), 100-116. doi:10.1016/j.concog.2011.10.015

Miele, D. B., Wager, T. D., Mitchell, J. P., & Metcalfe, J. (2011). Dissociating neural correlates of action monitoring and metacognition of agency. *Journal of Cognitive Neuroscience, 23*(11), 3620-3636. doi:10.1162/jocn_a_00052

Musek, J. (2017). The Overall Strength of the GFP. In *The General Factor of Personality* (pp. 183-202).

Norman, D. A., & Shallice, T. (1986). Attention to Action. In *Consciousness and Self-Regulation* (pp. 1-18).

Oakman, J. M., & Woody, E. Z. (1996). A taxometric analysis of hypnotic susceptibility. *Journal of Personality and Social Psychology, 71*(5), 980-991. doi:10.1037/0022-3514.71.5.980

Palfi, B., Parris, B. A., McLatchie, N., Kekecs, Z., & Dienes, Z. (2020). Can unconscious intentions be more effective than conscious intentions? Test of the role of metacognition in hypnotic response. *Cortex*. doi:10.1016/j.cortex.2020.11.006

Parris, B. A. (2017). The role of frontal executive functions in hypnosis and hypnotic suggestibility. *Psychology of Consciousness: Theory, Research, and Practice, 4*(2), 211-229. doi:10.1037/cns0000106

Parris, B. A., & Dienes, Z. (2013). Hypnotic suggestibility predicts the magnitude of the imaginative word blindness suggestion effect in a non-hypnotic context. *Consciousness and Cognition, 22*(3), 868-874. doi:10.1016/j.concog.2013.05.009

Perri, R. L., Rossani, F., & Di Russo, F. (2019). Neuroelectric evidences of top-down hypnotic modulation associated with somatosensory processing of sensory and limbic regions. *Neuroimage, 202*, 116104. doi:10.1016/j.neuroimage.2019.116104

Peter, B., Vogel, S. E., Prade, T., Geiger, E., Mohl, J. C., & Piesbergen, C. (2014). Hypnotizability, personality style, and attachment: an exploratory study, part 1-general results. *American Journal of Clinical Hypnosis, 57*(1), 13-40. doi:10.1080/00029157.2014.906152

Piccione, C., Hilgard, E. R., & Zimbardo, P. G. (1989). On the degree of stability of measured hypnotizability over a 25-year period. *Journal of Personality and Social Psychology, 56*(2), 289-295.

Piesbergen, C., & Peter, B. (2006). An investigation of the factor structure of the Harvard Group Scale of Hypnotic Susceptibility, Form A (HGSHS:A). *Contemporary Hypnosis, 23*(2), 59-71. doi:10.1002/ch.311

Preacher, K. J., & Coffman, D. L. (2006). Computing power and minimum sample size for RMSEA. In.

Pyka, M., Burgmer, M., Lenzen, T., Pioch, R., Dannlowski, U., Pfleiderer, B., . . . Konrad, C. (2011). Brain correlates of hypnotic paralysis-a resting-state fMRI study. *Neuroimage, 56*(4), 2173-2182. doi:10.1016/j.neuroimage.2011.03.078

R Core Team. (2013). R: A language and environment for statistical computing.

Raz, A., Fan, J., & Posner, M. I. (2005). Hypnotic suggestion reduces conflict in the human brain. *Proceedings of the National Academy of Sciences of the United States of America, 102*(28), 9978-9983. doi:10.1073/pnas.0503064102

Raz, A., Kirsch, I., Pollard, J., & Nitkin-Kaner, Y. (2006). Suggestion reduces the stroop effect. *Psychological Science, 17*(2), 91-95. doi:10.1111/j.1467-9280.2006.01669.x

Reise, S. P. (2012). The rediscovery of bifactor measurement models. *Multivariate behavioral research, 47*(5), 667-696.

Robin, B. R., Kumar, V. K., & Pekala, R. J. (2005). Direct and indirect scales of hypnotic susceptibility: resistance to therapy and psychometric comparability. *International Journal of Clinical and Experimental Hypnosis, 53*(2), 135-147. doi:10.1080/00207140590927617

Rosenthal, D. M. (2002). How many kinds of consciousness? *Consciousness and Cognition, 11*(4), 653-665. doi:10.1016/s1053-8100(02)00017-x

Rosenthal, D. M. (2006). Consciousness and Higher‐Order Thought. *Encyclopedia of cognitive science*. doi:10.1002/0470018860.s00149

Rosenthal, D. M. (2008). Consciousness and its function. *Neuropsychologia, 46*(3), 829-840. doi:10.1016/j.neuropsychologia.2007.11.012

Rosseel, Y. (2012). lavaan: AnRPackage for Structural Equation Modeling. *Journal of Statistical Software, 48*(2). doi:10.18637/jss.v048.i02

Schoenberger, N. E. (2000). Research on hypnosis as an adjunct to cognitive-behavioral psychotherapy. *International Journal of Clinical and Experimental Hypnosis, 48*(2), 154-169. doi:10.1080/00207140008410046

Semmens-Wheeler, R., Dienes, Z., & Duka, T. (2013). Alcohol increases hypnotic susceptibility. *Consciousness and Cognition, 22*(3), 1082-1091. doi:10.1016/j.concog.2013.07.001

Shor, R. E., & Orne, E. C. (1962). *Harvard group scale of hypnotic susceptibility*: Consulting Psychologists Press.

Shor, R. E., & Orne, E. C. (1963). Norms on the Harvard group scale of hypnotic susceptibility, form A. *International Journal of Clinical and Experimental Hypnosis, 11*, 39-47. doi:10.1080/00207146308409226

Spanos, N. P. (1971). Goal-directed fantasy and the performance of hypnotic test suggestions. *Psychiatry, 34*(1), 86-96. doi:10.1080/00332747.1971.11023658

Spanos, N. P., Cobb, P. C., & Gorassini, D. R. (1985). Failing to resist hypnotic test suggestions: a strategy for self-presenting as deeply hypnotized. *Psychiatry, 48*(3), 282-292. doi:10.1080/00332747.1985.11024288

Srzich, A. J., Cirillo, J., Stinear, J. W., Coxon, J. P., McMorland, A. J. C., & Anson, J. G. (2019). Does hypnotic susceptibility influence information processing speed and motor cortical preparatory activity? *Neuropsychologia, 129*, 179-190. doi:10.1016/j.neuropsychologia.2019.03.014

Tanaka, J. S. (1987). "How Big Is Big Enough?": Sample Size and Goodness of Fit in Structural Equation Models with Latent Variables. *Child Development, 58*(1). doi:10.2307/1130296

Terhune, D. B., Cardena, E., & Lindgren, M. (2011). Dissociative tendencies and individual differences in high hypnotic suggestibility. *Cognitive Neuropsychiatry, 16*(2), 113-135. doi:10.1080/13546805.2010.503048

Terhune, D. B., Cleeremans, A., Raz, A., & Lynn, S. J. (2017). Hypnosis and top-down regulation of consciousness. *Neuroscience and Biobehavioral Reviews, 81*(Pt A), 59-74. doi:10.1016/j.neubiorev.2017.02.002

Varga, K., Farkas, L., & Mero, L. (2012). On the objectivity of the scoring of Harvard Group Scale of Hypnotic Susceptibility. *International Journal of Clinical and Experimental Hypnosis, 60*(4), 458-479. doi:10.1080/00207144.2012.675298

Wagstaff, G. F. (1996). Methodological issues in hypnosis. *Psychological research: Innovative methods and strategies*, 202-220.

Weitzenhoffer, A. M., & Hilgard, E. R. (1962). *Stanford hypnotic susceptibility scale, form C* (Vol. 27). Palo Alto, CA: Consulting Psychologists Press.

Woody, E. Z., Barnier, A. J., & McConkey, K. M. (2005). Multiple hypnotizabilities: differentiating the building blocks of hypnotic response. *Psychological Assessment, 17*(2), 200-211. doi:10.1037/1040-3590.17.2.200

Xia, Y., & Yang, Y. (2019). RMSEA, CFI, and TLI in structural equation modeling with ordered categorical data: The story they tell depends on the estimation methods. *Behavior Research Methods, 51*(1), 409-428. doi:10.3758/s13428-018-1055-2

Yee, T. W. (2010). TheVGAMPackage for Categorical Data Analysis. *Journal of Statistical Software, 32*(10). doi:10.18637/jss.v032.i10

Yee, T. W. (2015). *Vector generalized linear and additive models: with an implementation in R*: Springer.

Zahedi, A., Abdel Rahman, R., Sturmer, B., & Sommer, W. (2019). Common and specific loci of Stroop effects in vocal and manual tasks, revealed by event-related brain potentials and posthypnotic suggestions. *Journal of Experimental Psychology: General, 148*(9), 1575-1594. doi:10.1037/xge0000574

Zahedi, A., Luczak, A., & Sommer, W. (2020). Modification of food preferences by posthypnotic suggestions: An event-related brain potential study. *Appetite, 151*, 104713. doi:10.1016/j.appet.2020.104713

Zahedi, A., & Sommer, W. (2021). How hypnotic suggestions work – critical review of prominent theories and a novel synthesis. doi:10.31234/osf.io/mp9bs

Zahedi, A., Stuermer, B., Hatami, J., Rostami, R., & Sommer, W. (2017). Eliminating stroop effects with post-hypnotic instructions: Brain mechanisms inferred from EEG. *Neuropsychologia, 96*, 70-77. doi:10.1016/j.neuropsychologia.2017.01.006

Zahedi, A., Sturmer, B., & Sommer, W. (2020). Can posthypnotic suggestions boost updating in working memory? Behavioral and ERP evidence. *Neuropsychologia, 148*, 107632. doi:10.1016/j.neuropsychologia.2020.107632

Running head: LOCI OF STROOP EFFECTS

Common and Specific Loci of Stroop Effects in Vocal and Manual Tasks, Revealed by Event-Related Brain Potentials and Post-Hypnotic Suggestions

Anoushiravan Zahedi[1], Rasha Abdel Rahman[1], Birgit Stürmer[2], Werner Sommer[1]

[1] Humboldt-Universität zu Berlin; [2] International Psychoanalytic University, Berlin

Author Note

This research was supported by a scholarship to A.Z. by the German Academic Exchange Service (DAAD)

We thank Mona Sprengeler for help in data acquisition, Ulrike Bunzenthal, Rainer Kniesche, Thomas Pinkpank, and Gianpiero Tari for technical support.

Correspondence concerning this article should be addressed to Anoushiravan Zahedi, Institut für Psychologie, Humboldt-Universität zu Berlin, Rudower Chaussee 18, 12489 Berlin, Germany.

E-mail: zahedian@hu-berlin.de

Raw data and supplementary materials:

https://osf.io/7z26y/

Abstract

In the Stroop task color words are shown in various print colors. When print colors are named or classified with button presses, interference occurs if word meaning is color-incongruent and facilitation if it is congruent. Although the Stroop effects in vocal and manual task versions are similar, it is unclear whether the underlying mechanisms are equivalent. We addressed this question by (1) recording event-related brain potentials (ERPs), (2) manipulating the lexicality of neutral stimuli, and (3) giving post-hypnotic suggestions (PHS) that written words would lose their meaning. The Stroop effect in the vocal version was twice its manual counterpart. PHS strongly reduced both effects by a similar amount, supporting a common semantic locus during reading. Task- and hypnosis-invariant lexicality effects for neutral words ruled out pre-semantic reading loci. Articulation-artifact corrected ERPs showed task-invariant Stroop effects in N400 amplitudes, supporting similar semantic loci. However, in the vocal task response-locked ERPs indicated a task-specific Stroop effect over left-inferior frontal and parietal scalp sites, suggesting interference during word production. Interestingly, PHS increased the N1 and decreased the N2 components in ERPs, regardless of congruency, indicating enhanced proactive executive control and diminished demands on conflict-monitoring, respectively. Stroop effects in the N400 were reduced by PHS, confirming their semantic locus. In conclusion, vocal and manual Stroop versions seem to share semantic loci of conflict. The bigger vocal Stroop effect may be due to additional loci during word production lexicon. Apparently, PHS diminish Stroop effects by enhancing proactive executive control over lexico-semantic conflicts.

Keywords: Stroop Effect, Executive control, Event-related potentials, post-hypnotic suggestions.

Common and Specific Loci of Stroop Effects in Vocal and Manual Tasks, Revealed by Event-Related Brain Potentials and Post-Hypnotic Suggestions

Whenever we enter a situation, which requires a set of new responses to successfully solve tasks posed by the environment, executive functions are required. A typical example is first-time switching to left-side traffic for experienced right-side drivers, which requires the inhibition of prepotent responses and replacing them with the appropriate ones. Or, for example, for the most part of human history, it was appropriate to give high priority to the consumption of high-calorie food, a behavior that, considering the dangers of obesity and the ubiquitous availability of rich food and snacks, must be inhibited by most members of modern affluent societies (e.g. Dohle et al., 2018; Guerrieri et al., 2008; Nederkoorn et al., 2009; Nederkoorn et al., 2010). From a scientific point of view, executive functions as a psychological structure were initially conceptualized to bridge the gap between short-term memory, as an inactive deposit (Atkinson & Shiffrin, 1968) and the central executive (Baddeley, 1996, 2003; Baddeley & Hitch, 1974), a homunculus supposed to actively process the material in working memory. An important point about executive functions is the question of their unity or diversity (Miyake et al., 2000), which has been studied extensively with many tools, ranging from performance measures (for review see Diamond, 2013; Miyake & Friedman, 2012; Miyake et al., 2000) to brain imaging (for review see Collette et al., 2005; Niendam et al., 2012; Yuan & Raz, 2014). Although the question of how many executive functions have to be distinguished, is still to be resolved, there is some agreement that next to inhibition, major executive functions are the updating of short-term memory and shifting between task sets (Diamond, 2013; Miyake & Friedman, 2012; Miyake et al., 2000).

A central idea about executive functions is the necessity for the de-automatization of behavior, that is, the inhibition of existing and prepotent responses (Diamond, 2013) before they can be substituted by more appropriate actions. Due to its importance in quotidian circumstances, many efforts have been made to enhance the inhibition of prepotent responses. For instance, physical exercise has had limited success in the enhancement of executive functions (Diamond & Ling, 2016); and although training of inhibition tasks had led to some enhancement, success was mostly limited to the trained task and did not transfer to other inhibition tasks (Thorell et al., 2009).

Recently, hypnosis or posthypnotic suggestions (PHS) have been proposed as a technique to overcome prepotent responses (Lifshitz et al., 2013). Thus, PHS have been shown to strongly diminish the Stroop interference effect. The classic Stroop effect – the impairment of performance in naming the print color of a word denoting a different color (e.g. *Red* printed in blue) – is seen to tap into the inhibition function. The Stroop effect is very persistent and hard to diminish, even by extensive exercise (MacLeod, 1991). The Stroop task is a paragon, where an extensively trained function (reading words), is prepotent but irrelevant and must be suppressed in order to replace it with the task-appropriate action (color naming).

The Stroop task is an important tool in different fields of cognitive psychology, including but not restricted to the study of cognitive control (Coderre & van Heuven, 2014; Hanslmayr et al., 2008; Ilan & Polich, 1999; Langenecker et al., 2004), and its development (Bub et al., 2006), impulsivity (Dickman, 1990), and Psycholinguistics (Dhooge & Hartsuiker, 2010, 2011; Geng et al., 2013; Shitova et al., 2016, 2017). In the present paper, we will administer PHS in order to manipulate executive functions as required in the Stroop task.

In the Stroop task, two kinds of information are simultaneously presented, task-irrelevant color words and the colors that the words are written in and that have to be responded to. If the word meaning is incongruent with the print color, for example, *green* written in red, reaction times (RT) to the print color are longer than when both are congruent, for example, *red* written in red (MacLeod, 1991). The difference in performance between incongruent and congruent trials is the Stroop effect. It is commonly accounted for by the automatic activation of the task-irrelevant meaning of the word, which is hard to suppress. In contrast, extracting the color information and executing an appropriate response appears to be more controlled and effortful (Kornblum, 1994; MacLeod, 1991). One important aspect of the Stroop task is the response task version, that is, whether the color is named (vocal task modality) or identified by pressing color-coded buttons (manual task modality) (MacLeod, 1991). Previously it has been shown that manual and vocal versions cause similar but somewhat disparate results. Thus, vocal Stroop effects are typically larger than manual effects (Liotti et al., 2000; Redding & Gerjets, 1977). More subtle differences are observable when different categories of neutral trials are used, such as strings of letters or characters (e.g. *LLLL* or *GGGG or %&*@*), general words (e.g. *while* written in blue), semantically associated words (e.g., *blood*, or *sky,* which are associated with the colors red and blue, respectively), and words that are semantically related to other colors which are not included in response set (e.g., *purple* when this color is not part of the response set). RTs for these neutral categories have been reported to differ only in vocal but not in manual Stroop task versions (Liotti et al., 2000; Redding & Gerjets, 1977; Sharma & McKenna, 1998).

It is our primary aim to understand the differences between vocal and manual Stroop task versions. To this aim, it is helpful to consider the three main accounts for the vocal Stroop effect. The first explanation asserts that the interference is due to the perceptual advantage of word reading, which is highly automatized; therefore, interference may occur at the perceptual level (Hock & Egeth, 1970). However, this account cannot explain the facilitation commonly observed in congruent relative to neutral words in the Stroop task.

The second account is based on language production theory (e.g., Dell, 1986; Levelt et al., 1999; Shitova et al., 2017). It postulates interference at the lexico-semantic level (Glaser & Glaser, 1989; Sharma & McKenna, 1998; Sugg & McDonald, 1994), integrating Stroop and Stroop-like effects in related paradigms. A prominent example of such a task is picture-word interference (PWI), where to-be-named pictures are shown together with words (Shitova et al., 2016; van Maanen et al., 2009). According to this account, both print color and word meaning activate corresponding lexical and semantic nodes; when two different but connected lexico-semantic nodes are activated, they compete for the selection of the appropriate lexical entry, causing a delay in processing.

Supporting evidence for this theory is obtained from recordings of the N400 component in event-related potentials (ERP). The N400 is a negative-going parieto-central deflection, which is typically larger in response to incongruent than congruent Stroop words. The N400 is considered as a cue for semantic processing (Hanslmayr et al., 2008; Liotti et al., 2000; West & Alain, 1999) and may be related to conflict detection but not conflict resolution (Coderre et al., 2011). Lexical competition in various tasks has also been associated with posterior ERP effects, starting already between 150 and 250 ms (e.g. Costa et al., 2009; Dell'acqua et al., 2010; Maess et al., 2002; Rose & Abdel Rahman, 2016; Strijkers et al., 2010).

As an alternative explanation, the *response exclusion theory* suggests that Stroop effects are located in the articulatory output buffer (Mahon et al., 2007). Because words have privileged access to this buffer, they have to be removed before the color or picture name can be articulated, and removal takes longer for related (incongruent) compared to unrelated or neutral trials. This theory predicts interference effects only when articulation is involved, that is, in the vocal task, but not in the manual task where articulators are supposedly not involved. However, in PWI tasks that have been frequently employed in research on language production, and considered as Stroop-like tasks (MacLeod, 1991; van Maanen et al., 2009), manual and vocal versions show highly similar interference effects in performance (Abdel Rahman & Aristei, 2010; Hutson et al., 2013). Supporting data for the response exclusion theory come from ERP studies of the Stroop task (Badzakova-Trajkov et al., 2009; Hanslmayr et al., 2008; Liotti et al., 2000; West & Alain, 1999), which have revealed not only larger N400 amplitudes in incongruent as compared to congruent conditions but also a larger late positive complex (LPC) at 600-800 ms after stimulus onset. In contrast to these relatively late effects there is no evidence for congruency effects in earlier components such as the N200 or P300 (Ilan & Polich, 1999) reflecting perceptual and classification processes, or in posterior modulation related to lexical selection. In addition, analyses of EEG in the Stroop task have shown that phase coupling lasts longer for incongruent trials in a late interval, possibly indicating conflict resolution at the response level (Hanslmayr et al., 2008).

The final account of Stroop effects is the *response conflict theory* (Botvinick et al., 2001; Cohen et al., 1990), suggesting that words and colors are perceived and processed in different systems and activate corresponding responses. In the Stroop task, only the response activated by the print color is appropriate. When response activations are congruent, there is mutual facilitation and the response is executed faster than when responses exclude each other in incongruent trials. In both cases, the appropriate response is executed after reaching a certain activation threshold, which takes longer for incongruent than congruent trials, yielding the Stroop effect (Botvinick et al., 2001; Cohen et al., 1990).

Further clues how vocal and manual Stroop versions differ come from neuroimaging studies. These studies have shown disparities between incongruent and congruent trials that are widely distributed over the brain. These areas include dorsolateral prefrontal cortices (Banich et al., 2000; Milham et al., 2003), precuneus (Banich et al., 2000), inferior frontal gyrus (Langenecker et al., 2004), anterior cingulate cortex, and posterior lateral prefrontal cortex (Milham et al., 2003). Beyond the prefrontal cortex Stroop trials differentially activate the left premotor cortex, left postcentral cortex, left putamen, supplementary motor area, right superior temporal gyrus, and bilateral peristriate cortices (Langenecker et al., 2004; Milham et al., 2003; Pardo et al., 1990; Peterson et al., 1999), indicating the involvement of multiple brain systems.

Figure 1 presents a heuristic model, summarizing the accounts of Stroop effects reviewed above, suggesting several loci of conflict that partially overlap and partially differ between vocal and manual Stroop tasks versions. It is plausible to assume that the words presented in both task versions – although by themselves task-irrelevant - are automatically processed in word recognition segments. However, only the vocal but not the manual version should contain a word production segment associated with articulatory processes.

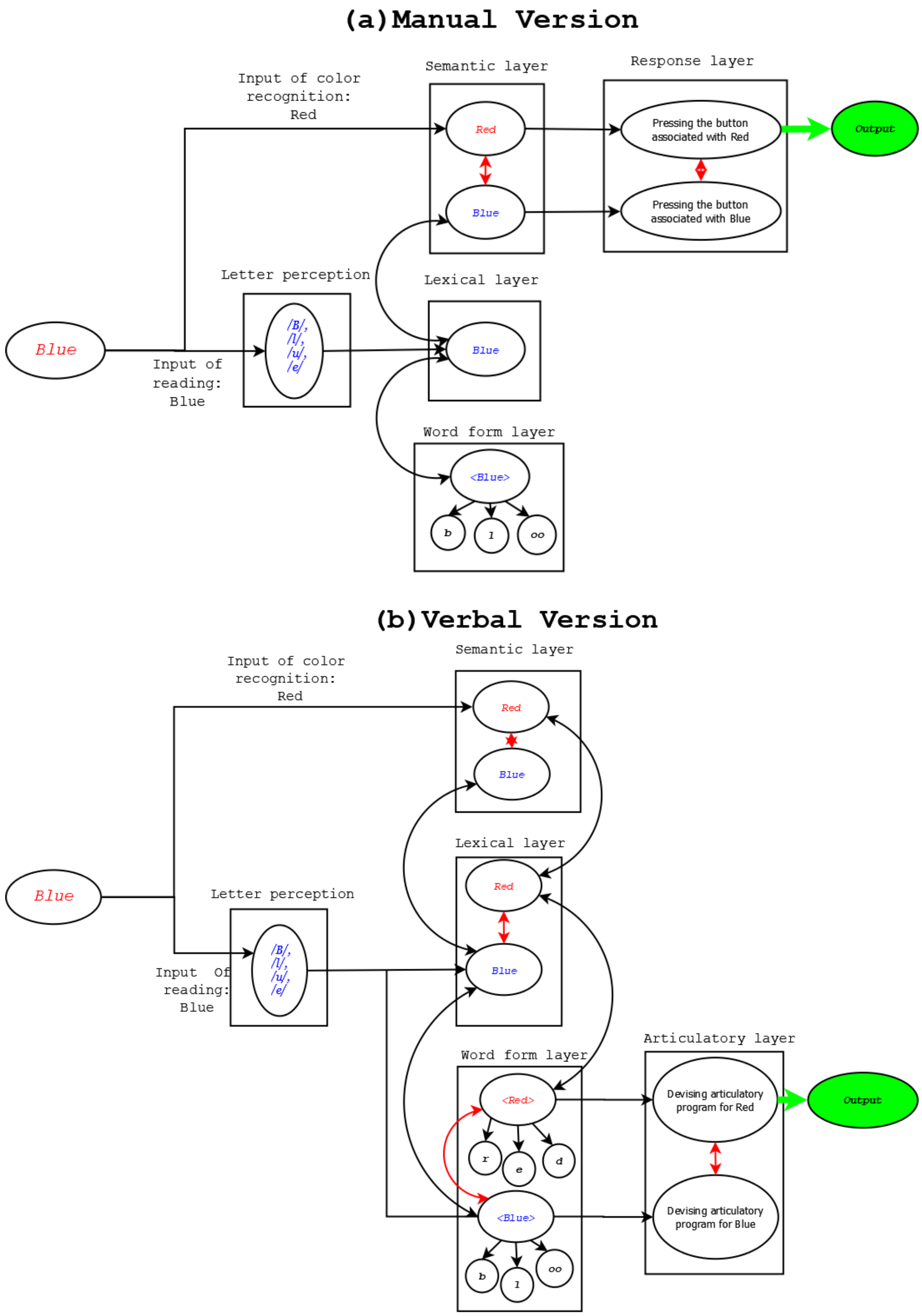


Figure 1. Schematic representation of cognitive processes and their interaction (red arrows) in Stroop tasks as suggested by different accounts. (a) In the manual Stroop task, interference and facilitation may occur between *semantic representations* or *response activations*. (b) In the vocal

Stroop task, interference and facilitation may occur at the *semantic*, *lexical, word form,* or *articulation* level.

The heuristic model suggests that color-based information will activate a semantic node in both task versions; simultaneously, the written word will activate a *lexical representation*, which in turn will activate both *semantic representations* as well as *word form representations*. In the manual task version, the response consists in pressing a button associated with the perceived print color. Therefore, the response should be based on the activated node in the *semantic representation layer*. Interference and facilitation in the manual version can arise both at the semantic and the response level. In the vocal version the response consists in naming (articulating) the print color. This response should be based on the activated node at the *word form level*. Hence, the semantic node corresponding to the print color should activate a lexical/semantic node and then the corresponding word form. This activation flow in the vocal version provides additional potential loci of interference between the activation based on word meaning and color processing in comparison to the manual version within the word production system.

One of the most salient aspects of the Stroop effect is its consistency and persistence even after large amounts of practice (MacLeod, 1991). Given the robustness and automaticity of the Stroop effect it is striking that it can be strongly diminished or even eliminated under the impact of post-hypnotic suggestions (PHS) inducing “hypnotic agnosia” in hypnotizable participants (Lifshitz et al., 2013; Raz et al., 2003; Raz et al., 2007; Raz & Shapiro, 2002; Zahedi et al., 2017). Zahedi et al. (2017) have provided EEG evidence that the impact of PHS may relate to enhanced cognitive control. More specifically, the effect of PHS, which induces hypnotic agnosia, might be located at 1) letter perception, 2) *lexical representation layer*, 3) *semantic* *representation layer* and/or 4) *response production* - although it may seem far-fetched that participants would access the meaning of the words but not show the Stroop effect. Presumably, the impact of PHS would propagate through the cognitive system, that is, an impact at a low level would preclude or attenuate interference or facilitation at higher levels.

The primary aims of the present study were to functionally localize the Stroop effects in vocal and manual task versions and the mechanisms underlying their modulations by post-hypnotic suggestions. In pursuing these aims, we used a counterbalanced design including vocal and manual Stroop task versions, with and without PHS. In both task versions we used several categories of stimuli. Beside congruent and incongruent trials, different neutral conditions were employed: non-words, produced by scrambling real German words (e.g. *Tasdt* or *Hcbu*), high- and low-frequency color-unrelated words (e.g. *Buch* or *Karte vs. Seide* or *Kurve*). The recoding of event-related brain potentials (ERPs) provided insight into effects on specific neurocognitive processes with high time resolution.

Based on the previous findings, integrated in the heuristic model (Fig. 1), we expected for the **manual** Stroop task version both facilitation (differences between congruent and non-words), and interference (differences between incongruent and non-words) located in semantic representations. In contrast, we did not expect performance differences between the different neutral conditions (non-words, low- and high-frequency words), aimed at manipulating lexical representations of word processing. In the **vocal** Stroop task version, we expected not only facilitation and interference at the semantic level but also lexicality effects. Lexicality effects are due to activation of competing nodes at the lexical representation layer, which have to be overcome before planning the overt response. In comparison to the manual task version both facilitation and interference effects in performance should be more pronounced in the vocal task, because of, first, additional possible loci of interactions between the color-perception and word recognition pathways, for instance, in the lexical and articulatory stages of word production, and second, because of possible backpropagations, for example, from word form and lexical layer to semantic and lexical layers. Such backpropagations might lead to qualitatively different, but also stronger interactions between two pathways.

In ERPs studies, the investigation of vocal Stroop tasks is problematic because of the strong articulation artifacts superimposing late cognitive ERP components such as the N400. However, recent methodological advances allow overcoming this problem. Thus, Ouyang et al. (2016) have developed a method that separates brain-derived ERPs from overlapping articulation artifacts. Applying this method, we expected larger N400 amplitudes for incongruent than congruent trials in both task versions because of the presumed impediment of lexico-semantic access in the former.

In addition, we analyzed conflict-related components, in particular the N1 (or N100) (Zinchenko et al., 2017), and the N2 (or N200) (Folstein & Van Petten, 2008; Yeung et al., 2004). As N1 and N2 are conflict-related components (Yeung et al., 2004), one might expect that they will be affected by congruency in the Stroop task. However, previous ERP studies of Stroop effects did not detect any congruency effects in these early components (Badzakova-Trajkov et al., 2009; Coderre et al., 2011; Coderre & van Heuven, 2014; Hanslmayr et al., 2008; Ilan & Polich, 1999; Liotti et al., 2000; West & Alain, 1999). PHS were expected to change tasks performance, in other words, the amount of conflict and the resolution of this conflict. Given that PHS effects may be due to proactive control, one may expect similar changes due to PHS in these early components, equivocally for all congruency conditions. However, because of the uncertainty about the nature of these two components, it is hard to suggest a specific direction of amplitude (or latency) changes.

Based on mentioned studies, the P3 is usually divided to subcomponents, the P3a with a frontal distribution and the P3b with a central-posterior distribution. Although the P3a has been related to stimulus processing, and especially novelty detecting, the P3b has been related to attentional allocation and context updating operations (Polich, 2007). If we consider P3b as a component related to attentional allocation (or stimulus relevance), there are two possible effects of PHS on this component. First, if participants cannot read the words at all, congruency effects might be extinguished under the effects of PHS, greatly diminishing the P3b amplitude in all conditions. However, if participants allocate their cognitive resources more efficiently under the influence of PHS, allocating attention to specific stimulus categories may ensue, possibly increasing any congruency effects in the P3b component.

Response-locked ERPs are synchronized to the time of response onset, instead of stimulus onset (Ouyang, Schacht, Zhou, & Sommer, 2013; Zhang, 1998). Response-locked ERPs enable focusing on response production-related processes, which in stimulus-locked ERPs tend to be smeared and reduced in size because of their latency variability. Especially, when comparing two tasks with different output modalities, it is of great interest to distinguish their response-production processes. By and large, the manual and vocal versions of the Stroop task, can be considered as different tasks largely because they differ in output modalities. However, it is a matter of debate whether the different Stroop task versions are similar (Dhooge & Hartsuiker, 2010, 2011; Geng et al., 2013) or different (Liotti et al., 2000; Redding & Gerjets, 1977; Sharma & McKenna, 1998). Hitherto this question was hard to address with ERPs because of the articulation artifact typically arising during overt naming, a problem that was resolved in the current study by applying the RIDE method (Ouyang et al., 2016). Please note that we refrained from calculating the lateralized readiness potential (Coles, 1989) because we did not have enough trials and in the vocal task the response is not lateralized, as required for calculating this component.

Post-hypnotic suggestions aimed at disabling participants to understand or, more generally, read the task-irrelevant words. Therefore, PHS should affect the word recognition pathways (see Fig. 1) and we conceived of four plausible scenarios in this condition.

(1) If cognitive control invested under the impact of the PHS, prevents or impedes *letter perception*, any performance differences within both manual and vocal version, for example, between word categories, including the different neutral categories, or between the congruent and incongruent trials should be diminished relative to the standard condition or even abolished.

(2) If PHS still allow the activation of *lexical word representations* but excessive utilization of cognitive control inhibits or blocks the competition between the activated nodes, at least in the vocal task version, RTs to non-words should be shorter than for both high- and low-frequency neutral word. Since in the manual version there should be no performance differences between non-words, and high- and low-frequency neutral words, as there is no interaction between these two pathways at the lexical level, PHS should have no impact. However, any N400 differences between these conditions seen without PHS should be attenuated or eliminated by PHS.

(3) If cognitive control induced by PHS is directed only to the *semantic or later levels*, one would expect the effects at the pre-semantic levels in the vocal version to be preserved. Specifically, in neutral trials RTs should not only show a lexicality effect (i.e., shorter RTs to non-words than to words), but also a frequency effect (i.e. shorter RTs to high- than low-

frequency word trials). Please note, however that word frequency effects in PWI task is usually reversed (e.g., Burt & Tate, 2002; Catling et al., 2010; Dhooge & Hartsuiker, 2010; Miozzo & Caramazza, 2003). In addition, the N400 component should differ between these neutral word categories.

Moreover, in this scenario of semantic or post-semantic effects of PHS the vocal version should show some residual facilitation and interference effects that should not be observed in the manual version, mainly due to the existence of lexical and word form layers. Overall, however, facilitation and interference effects should decrease after PHS in comparison to the no-hypnosis condition both in ERPs and RTs.

(4) In case that PHS impact the response level, that is, hand selection in the manual version and word production in the vocal version, we expect that performance in both vocal and manual versions will be enhanced, which might be reflected in late ERP components preceding the response. In addition, if PHS would exclusively affect the response level, we would expect that all differences in pre-response ERPs – especially in the N400 component – would be indifferent to PHS.

Method

Participants

The sample consisted of highly hypnotizable participants, selected by screening with the Harvard Group Scale of Hypnotic Susceptibility- Form A (HGSHS-A) (Shor & Orne, 1962) translated into German (Bongartz, 1985). Each screening session included up to 10 volunteers. Of 122 screened volunteers (*M* = 28.7 years; range = 18-76, *SD* = 12.9), 24 were highly hypnotizable (> 8/12 points) (*M* = 30.2 years; range = 18-63, *SD* = 13.8); of these persons, 16 (11 women) participated in the present experiment (*M* = 31.1 years; range = 19-63, *SD* = 14.4).

None of these participants had color vision impairments (Ishihara, 1996) or a history of diagnosed dyslexia. Participation was compensated either with course credits or 8 € per hour. The study had been approved by the Ethics Committee of the Department of Psychology at the Humboldt-Universität zu Berlin and written informed consent was obtained prior to both the screening session and the main experiment.

Materials and Instructions

Stroop task. The Stroop task was programmed in Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com). It consisted of five different categories of trials, including congruent (e.g. *Red* written in red) and incongruent (e.g. *Red* written in blue) trials for four different color words (red, green, blue, and yellow), 32 non-words (scrambled words, e.g. *Tatge, Uglpf, Khcle*), 32 high-frequency German words (e.g. *Gott, Recht, Frau, Kurs,* mean word form frequency = 0.3 ± 1.0 per mio; (Geyken, 2007)), and 32 low-frequency German words (e.g. *Trank, Backe, Basar, Halm;* mean word form frequency = 3.5 ± 1.1). Non-words were actual words scrambled and checked to be non-pronounceable. Non-color materials were matched in length to the color words. Non-color words were unrelated to color names of any kind (even if not included in the response set). The first letters of the neutral words differed from the first letters of the target responses (color names) in order to avoid phonological facilitation (Levelt, 1999; Levelt et al., 1999; Levelt et al., 1991). Each category contained 64 trials obtained by repeating each high- and low-frequency word and non-word once, and each color word 16 times in the congruent and incongruent condition, yielding 320 trials in total.

At a viewing distance of 70-80 cm, visual angle of the words was ±1.5 degrees; luminance of the stimuli was set to 30-35 cd/m^2. The words were presented on the screen in red [RGB: 240, 40, 40], green [RGB: 40, 240, 40], blue [RGB: 40, 40, 240], or yellow [RGB: 240, 240, 40]. Each of the four colors was used 80 times distributed equally across all stimulus categories. The background screen was gray [RGB:100, 100, 100].

The task was administered with two different response modalities. In the manual Stroop version, each of the four colors was associated with one of four response keys in a fixed way across all participants. This association was to be memorized at the beginning of the experiment but could be refreshed if needed by looking at the response keys, which were placed on the table in front of the participant. The keys were operated with the index and middle fingers of both hands. In the vocal Stroop version participants named the print color of the stimuli. To identify the spoken response we used the voice recognition plug-in of Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com), and the dictionary of the four color words used was set to a certainty level of 95%. If the software could not recognize the spoken word the corresponding trial was classified as missing. Voice onset was used as reaction time (RT) in the vocal version.

At the beginning of a trial a fixation cross was shown for 500 ms; the maximum duration of a trial was 2000 ms, after which the trial was considered as an error and the next trial started. Performance in the two tasks was measured as follows. For the manual task, RTs were defined as interval between stimulus onset and the onset of the button press. Pressing a wrong button or not responding before the 2-s deadline, was scored as an error. For the vocal task, the interval between stimulus onset and onset of voice detection was calculated as RTs. Wrong answers or answers after 2 s were coded as incorrect. In both task versions, trials with errors were excluded from RT analysis. RTs for correct responses, were treated as continuous variables.

At the beginning of each Stroop task version, 30 to 45 practice trials were conducted, providing feedback about response correctness. Each task took approximately 30 min, including three equally spaced breaks.

Hypnosis and Post-Hypnotic Suggestions. The hypnotic state is characterized by three distinct properties, concentration, dissociation, and suggestibility (Elkins et al., 2015; Jensen et al., 2017; Nash, 2005). In the current study Hypnosis and PHS were similar to our previous study (Zahedi et al., 2017). The hypnosis procedure, composed of induction, deepening, suggestions, and termination phases (Hammond, 1990, 1998), included PHS (given here in translation) as follows:

" After termination of hypnosis, you will participate one more time in the task, which you have done before. After I clap my hands, although you will see the words crisp, sharp and brilliant, their meaning will drown or burn, and they will seem to be meaningless nonsense, looking like words from a foreign language. Then, you can choose the color in which the words have been written as fast as possible. After I clap my hands a second time everything will come back to normal, as it was before." (Zahedi et al., 2017).

The PHS employed in the current study induces agnosia of the words while participants are awake, without requiring any hypnosis-like trance state. It is noteworthy, that in the present study, instead of hand clapping, we used a bell ring, providing a more constant sound. Accordingly, we instructed participants that they would hear a bell ring, and afterwards, the PHS were activated with a bell ringing. Here, hypnosis differed from commonly used procedures in two ways. First, suggestions were presented as audio-recording, except when it was absolutely necessary for the experimenter to intervene and present further suggestions; these interventions were only directed to further deepen hypnosis and were unrelated to the PHS. Second, there were two different versions of the imaginary condition during the hypnosis narration – either a beach or a forest scenario – which each participant could select at the beginning of the experiment.

Design and Procedure

The experiment consisted of two sessions, counterbalanced in order. One of the sessions entailed hypnosis (PH session), during which the PHS were given; the other session was without hypnosis (NH session). Within each session, both manual and vocal Stroop tasks were administered also in counterbalanced order. During hypnosis participants were seated in a reclining chair outside of the electrically shielded and sound-attenuated experimental chamber in which the tasks including EEG recordings were performed.

In the PH session, participants were first prepared for EEG recordings (see below) and then went through hypnosis, including PHS. Subsequently, they completed both versions of the Stroop task. Finally, a calibration phase recorded examples of eye-movement artifacts to be used in offline corrections. The PH session took approximately 3 hours. In the NH session – taking about two hours – everything was the same as in the PH session, except that there was no hypnosis. For each participant, the order of tasks was the same in both sessions.

Mean RTs were calculated for each participant and each condition, excluding incorrect responses, RTs < 150 and > 2000 ms, and RTs > 3 SDs per condition and participants. Less than five percent of the performance data had to be discarded.

EEG Recording

EEG was recorded from 60 Ag/AgCl electrodes, mounted in an elastic cap (Easy Cap, FMS GmbH, München, Germany), according to the 10-20 international system. The vertical electrooculogram was measured from two electrodes attached below each eye and the horizontal EOG was recorded from electrodes placed at the outer canthi. Two linked electrodes, placed at the mastoids, served as reference. The recording was conducted with Brainamps DC amplifiers (Brain Products GmbH, München, Germany), at a sampling rate of 1000 Hz; no additional filters were used during the recordings. Impedances of all electrodes were kept below 5 kΩ. Triggers for stimuli and responses were inserted online into the EEG data by synchronization between Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) and BrainVision Recorder (Brain Products GmbH, München, Germany).

Offline, EEG data were recalculated to average reference. Eye movement artifact correction was based on the recorded examples of horizontal and vertical eye-movements and blinks and calculated in BESA Research 6.0 program. The rectifier matrixes were produced for each participant separately and applied to their EEG recordings by linear derivation method. The data were band pass filtered with 0.05-40 Hz and inspected for any remaining sections with observable artifacts; these sections were excluded from further analyses. Data were segmented, averaged and analyzed with EEGLAB (Delorme & Makeig, 2004). During averaging, speech artifacts in the vocal Stroop task were corrected by using the RIDE plug-in (Ouyang et al., 2013; Ouyang et al., 2016). All segments with other artifacts, and/or incorrect or missing responses were eliminated, resulting in a loss of less than 10% of all trials.

For ERP components N1, N2, and P3, in the averaged signals per condition, were calculated after down-sampling to 250 Hz, as average amplitudes during specific time-windows (for exact time-windows of each component please see the corresponding section in the results). For the N400 component, which is a difference-component, the averaged-reference signals of two conditions were subtracted point-by-point, and then averaged to calculate the component as average amplitudes of the difference wave during the 420 to 500-ms interval.

Data Analyses

For statistical analyses, repeated-measures analysis of variance (ANOVA) was used, including the factors task version (vocal vs. manual task version), suggestion (with or without hypnosis), and either congruency (congruent, incongruent and average of all neutral conditions), or lexicality (letter strings, low- and high-frequency words). For ANOVAs of ERP data the additional factor electrode was applied. Whenever sphericity assumptions (tested with Mauchly's sphericity test) was violated, the Huynh-Feldt correction for degrees of freedom was used and indicated by the correction factor ε. For posthoc comparisons, we used Bonferroni-corrected contrasts unless stated otherwise.

Results

Behavioral Performance

Stroop effects. Table 1 present mean RTs. There were strong Stroop effects (incongruent vs. congruent), interference (incongruent vs. neutral), and facilitation (congruent vs. neutral) in the NH sessions; these effects were substantially reduced in the presence of PHS. This was confirmed by repeated measure ANOVA with factors task version, suggestion, and congruency. The main effects of congruency was highly significant, $F(2, 30) = 130.7$, $p < .000$, $\eta_p^2 = .89$, as was its reduction by PHS, $F(2, 30) = 37.9$, $p < .001$, $\eta_p^2 = .71$. There was also a main effect of suggestion, $F(1, 15) = 5.6$, $p < .05$, $\eta_p^2 = .27$, probably due to the massive reduction of RTs for incongruent trials in the PHS condition. The Stroop effect was larger in the vocal than in the manual task, reflected in the interaction between congruency and task version, $F(2, 30) = 10.9$, $p < .001$, $\eta_p^2 = .42$. Finally, a three-way interaction between task version, suggestion and congruency, $F(2, 30) = 3.99$, $p < .05$, $\eta_p^2 = .21$, indicated that the reduction of the Stroop effect in the PHS condition was more pronounced in the vocal task version. Interestingly, the main effect of task version was not significant, despite reflecting manual and vocal reaction times.

Table 1

Mean reaction times as a function of suggestion and congruency in manual and vocal Stroop task versions (SDs in parentheses)

Task version	Suggestion	Congruent	Incongruent	Sum of Neutrals	Neutral Letters	High-Frequency	Low-Frequency
Manual	NH	619.1 (140)	725.4 (174)	654.6 (139)	650.2 (134)	654.0 (142)	660.3 (147)
	PHS	618.0 (141)	663.6 (148)	633.5 (133)	628.0 (132)	634.2 (139)	639.1 (132)
Vocal	NH	606.4 (134)	789.9 (167)	663.4 (138)	660.1 (136)	662.2 (139)	668.1 (139)
	PHS	613.6 (129)	701.8 (132)	648.2 (128)	642.7 (128)	647.1 (128)	655.2 (131)

NH = no hypnosis; PHS = post-hypnotic suggestions

In order to follow up the interactions above, we calculated a repeated measures ANOVA just for the Stroop effects, that is, for the difference between congruent and incongruent conditions, with two levels of task version and two levels of suggestion. Again, task version, $F(1, 15) = 15.9$, $p = .001$, $\eta_p^2 = .51$, and suggestion, $F(1, 15) = 55.9$, $p < .001$, $\eta_p^2 = .78$, yielded main effects and interacted, $F(1, 15) = 4.5$, $p = .05$, $\eta_p^2 = .23$. Elucidating the interaction between suggestion and task version with congruency, we analyzed the task version-dependency of the Stroop effect for each suggestion separately. The Stroop effects differed significantly between the vocal and manual task versions, both in the NH session, $F(1, 15) = 14.3$, $p < .01$, $\eta_p^2 = .49$, as well as in the PHS session, $F(1, 15) = 9.6$, $p < .01$, $\eta_p^2 = .32$ (Table 2).

Next, we separately analyzed the components of the Stroop effect, that is, facilitation (the difference between congruent and neutral trials) and interference (the difference between incongruent and neutral trials). As to be expected interference was affected by task version, $F(1, 15) = 7.4$, $p < .05$, $\eta_p^2 = .33$, suggestion, $F(1, 15) = 27.5$, $p < .001$, $\eta_p^2 = .64$, and by the interaction of both factors, $F(1, 15) = 4.7$, $p < .05$, $\eta_p^2 = .23$. Further, whereas task version affected interference in the NH session, $F(1, 15) = 8.2$, $p = .01$, $\eta_p^2 = .35$, it dropped to a trend in the PHS session, $F(1, 15) = 3.6$, $p = .075$, $\eta_p^2 = .19$.

Similar to interference, the facilitation component of the Stroop effect was stronger in the vocal than in the manual task version, $F(1, 15) = 5.6$, $p < .05$, $\eta_p^2 = .27$, and was diminished by PHS, $F(1, 15) = 14.3$, $p < .005$, $\eta_p^2 = .48$. Importantly, in contrast to interference, facilitation was not differentially affected by hypnosis in the two task versions ($F < 1$).

Table 2

Mean Stroop effects as a function of Suggestion condition and Congruency in Stroop task and difference of Stroop effect as a function of task version (SDs in parentheses).

Task version	Suggestion	Stroop Effect	Difference of Stroop Effect	Interference Effect	Facilitation Effect
Manual	NH	106.3 (56)	60.6 (49)	70.7 (54)	35.5 (27)
	PHS	45.6 (30)		30.0 (26)	15.5 (25)
Vocal	NH	183.4 (69)	95.2 (56)	126.3 (56)	57.0 (41)

Task version	Suggestion	Stroop Effect	Difference of Stroop Effect	Interference Effect	Facilitation Effect
	PHS	88.1 (40)		54.1 (31)	33.9 (38)

NH = no hypnosis; PHS = post-hypnotic suggestions
Note 1. Stroop effect: Mean RTs for incongruent minus congruent conditions.
Note 2. Difference of Stroop effect: Stroop effect of NH minus Stroop effect of PHS.

Finally, we separately tested mean RTs within the incongruent, congruent, and neutral trials for a more detailed understanding of the effects reported above. In the NH session mean RTs for incongruent trials differed significantly between vocal and manual task versions, $F(1, 15) = 4.3$, $p = .05$, $\eta_p^2 = .22$, but in the PHS session they did not, $F(1, 15) = 1.4$, $p > .1$, $\eta_p^2 = .08$. Mean RTs of congruent and all neutral conditions were not significantly different between manual and vocal version (always $F < 1$). Hence, the observed interactions effects above seemed to be strongly driven by the very long RTs in the incongruent condition of the vocal task.

Lexicality effect. In order to assess whether the access to the lexicon is differentially involved in the two Stroop task versions and constitutes a locus of PHS effects we conducted repeated-measure ANOVAs for the factors lexicality (letter strings, high- and low-frequency words), task version, and suggestion. Although the main effect of lexicality in these neutral conditions was significant, $F(2, 30) = 3.3$, $p < .05$, $\eta_p^2 = .17$, there were no main effects of task version ($F < 1$), suggestion, $F(1, 15) = 1.8$, $p > .1$, $\eta_p^2 = .11$, or any interactions. In pairwise post-hoc comparisons, only the difference between low-frequency neutral words and letter strings was a strong trend, $F(1, 15) = 4.1$, $p = .06$, $\eta_p^2 = .21$, whereas the two other comparisons failed significance.

Error rates. Error rates are presented in Table 3. ANOVA with factors suggestion, task version and congruency (incongruent, congruent, sum of neutrals) revealed a main effect of congruency, $F(2, 30) = 13.7$, $p < .000$, $\eta_p^2 = .47$, but neither main effects of suggestion, $F(1, 15) = 1.7$, $p > .1$, $\eta_p^2 = .10$, task version, $F < 1$, nor any interactions. Finally, we tested the error rates in the three neutral conditions (factor lexicality) with the additional factors task version and suggestion. Similar to the RT results, lexicality yielded a main effect, $F(2, 30) = 7.7$, $p < .01$, $\eta_p^2 = .34$, but no other effects were significant.

Table 3

Error rates as a function of Suggestion and Congruency in Stroop task (SDs in parentheses)

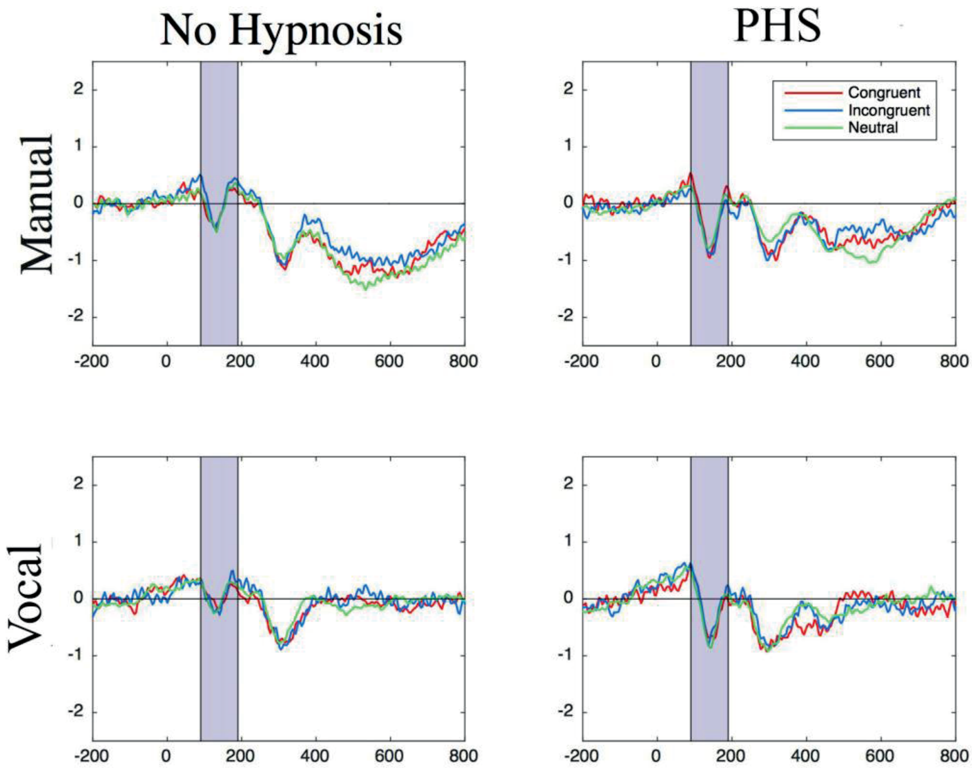
Task version	Suggestion	Congruent	Incongruent	Sum of Neutrals	Neutral Letters	High-Frequency	Low-Frequency
Manual	NH	3.2 (3.4)	4.2 (2.8)	5.5 (3.5)	6.7 (5.7)	5.9 (3.9)	3.9 (3.1)
	PHS	5.1 (6.0)	6.7 (7.8)	6.6 (5.5)	6.0 (4.7)	5.9 (5.7)	7.8 (8.2)
Vocal	NH	2.0 (3.4)	5.3 (4.2)	5.2 (4.6)	8.7 (8.6)	3.9 (4.0)	3.1 (3.2)
	PHS	1.5 (3.4)	7.6 (9.5)	5.9 (6.8)	8.5 (10.3)	4.6 (6.2)	4.6 (5.0)

NH = no hypnosis; PHS = post-hypnotic suggestions

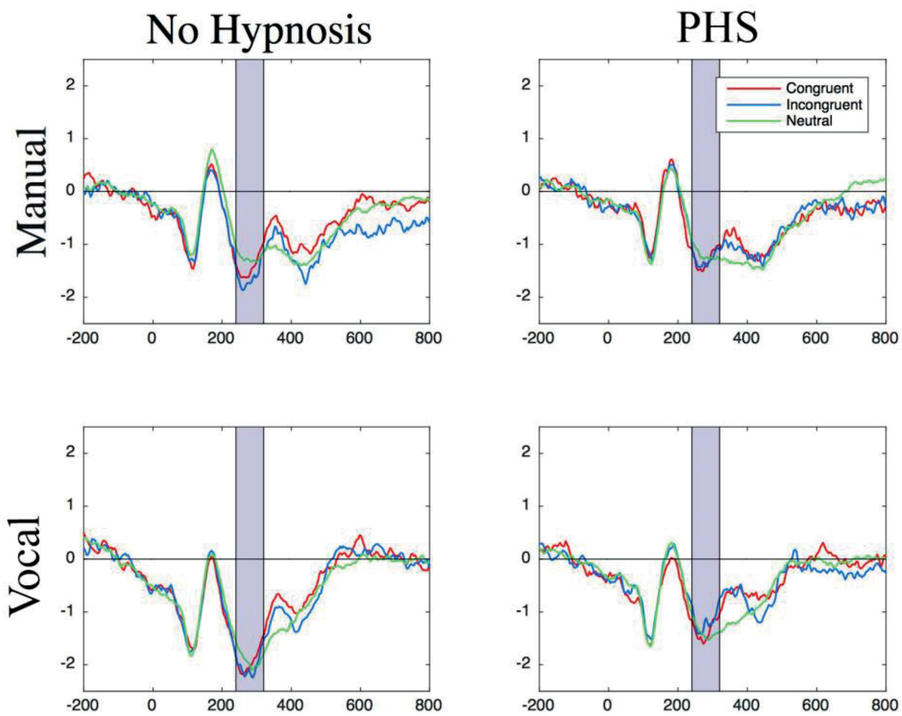
Event-related Potentials

In order to functionally localize the Stroop effects, their constituents and modulation by PHS, ERP components were analyzed. First, we assessed the N400, which has been frequently reported to be modulated by Stroop conditions, as reviewed in the Introduction. Next, we analyzed the amplitudes of the preceding N1 and N2 components. The N2 has been related to the processing of cognitive conflicts (Folstein & Van Petten, 2008) and might therefore be affected by Stroop task conflicts. Based on visual inspection of the ERPs we also analyzed the P300 component. Finally, in order to check for response-related loci, we evaluated response-locked ERPs. As none of the differences between different neutral categories were significant, we refrained from treating them as separate categories.

N1 and N2 components. Based on our hypothesis and observations of hypnosis effects in the ERPs, we analyzed the amplitudes of the N1 (first negative peak at Fz electrode around 120 ms; Fig. 2a) and the N2 (second negative peak in Cz electrode about 250 ms; Fig. 2b). An ANOVA of N1 amplitudes for the 120-160 ms time-window at Fz including the factors task version, suggestion and congruency (incongruent, congruent, neutral), revealed significantly smaller amplitudes in the NH than in the PHS (M = -.14 vs. -.59 μV) session, $F(1, 15) = 4.7$, $p < .05$, $\eta_p^2 = .24$. The N2 amplitude was calculated as average voltage of the signal between 200-300 ms at Cz, with the same ANOVA as above. There was a main effect of suggestion with a larger amplitude during NH than PHS (M = -1.58 vs. -0.98 μV), $F(1, 15) = 5.1$, $p < .05$, $\eta_p^2 = .25$. And further, no other main or interaction effects were significant.


No Hypnosis
PHS
Manual
Vocal
Congruent
Incongruent
Neutral
2
1
0
-1
-2
-200
0
200
400
600
800

(a)


No Hypnosis
PHS
Manual
Vocal
Congruent
Incongruent
Neutral
2
1
0
-1
-2
-200
0
200
400
600
800

(b)

Figure 2. Grand average ERPs. (a) Fz electrode, where the N1 component (shaded area) is significantly larger in the PHS than NH session; (b) Cz electrode, where the N2 component (shaded area) is significantly smaller in the PHS than NH session.

P3 component. Figure 2b shows a conspicuous difference between neutral and both congruent and incongruent trials, between about 300 and 400 ms, with a larger parietal positivity relative to the neutral condition. We calculated the average voltage of the signal in the 340-440 ms window at CPz (Fig. 3a), an electrode which represents the center of the posterior P3b component (Polich, 2007). With the same ANOVA, as used for the N1 and N2, we found strong main effects of task version, $F(1, 15) = 14.6$, $p < .005$, $\eta_p^2 = .49$, and congruency, $F(2, 30) = 15.4$, $p < .001$, $\eta_p^2 = .50$. Post-hoc contrasts confirmed that the congruency effect stemmed from smaller P3 amplitudes in the neutral relative to both congruent, $F(1, 15) = 46.3$, $p < .001$, $\eta_p^2 = .75$, as well as incongruent conditions, $F(1, 15) = 14.6$, $p < .005$, $\eta_p^2 = .49$, whereas congruent and incongruent conditions did not differ ($F = 1.0$). No other main effects or interactions were significant.

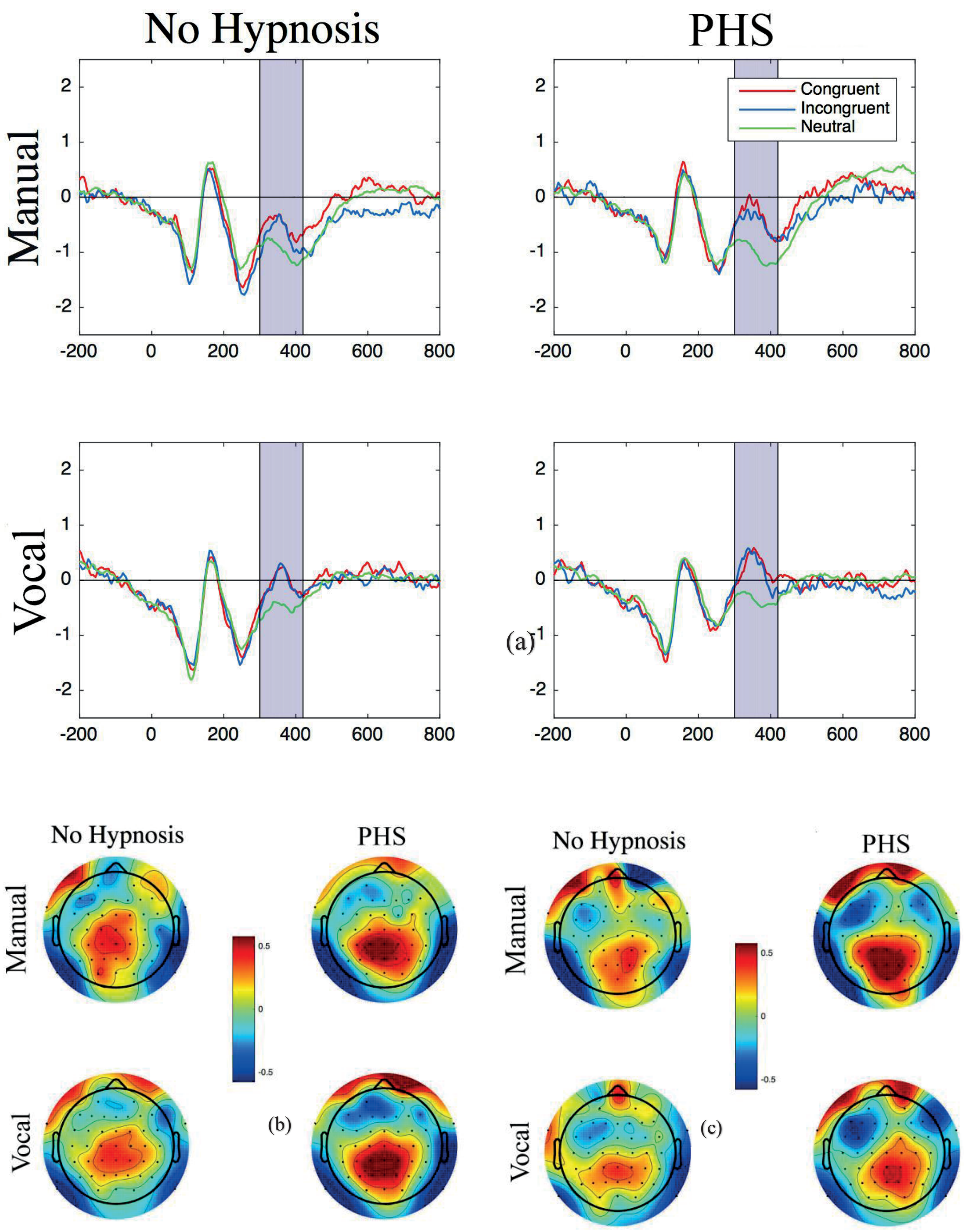


Figure 3. (a) Grand average ERPs at the CPz electrode; the shaded area marks the P3 component. Topographies of difference-waves (b) congruent - neutral trials and (c) incongruent - neutral trials in the 340-440 ms time-window.

Based on topographies of difference-wave (Fig. 3b), we also used a ROI (P3, P1, Pz, P2, P4, CP3, CP1, CPz, CP2 and CP4) and calculated the difference between congruent and neutral trials in the 360-440 ms time-window. ANOVA with factors task version, suggestion, and electrode revealed main effects of electrode, $F(9, 135) = 3.7$, $p < .005$, $\varepsilon = .41$, $\eta_p^2 = .17$, and suggestion, $F(1, 15) = 4.6$, $p < .05$, $\eta_p^2 = .23$, due to a larger congruency effect (the bigger differences between congruent-neutral and incongruent-neutral) under PHS compared to NH.

N400 component. Previous research found a centrally distributed N400 component around 450 ms elicited by incongruent relative to congruent Stroop task conditions (Liotti et al., 2000). As can be seen in the grand average ERPs in Figure 2.b and 3a, and the difference topographies between incongruent and congruent conditions (Fig. 4), similar effects were also present around 450 ms in both task modalities. But with deliberations into the same figures (Fig. 2b, 3a) it is obvious that the previously discussed P3 effect in the neutral condition extends also into the 420-500 ms time-window, rendering any results or interpretations of the effects in the N400 segment, which includes the neutral condition problematic. Therefore, for the sake of a clear interpretation, we omitted the neutral condition for the N400 analyses and also for the response-locked ERPs. This observation was verified in average ERP amplitudes between 420 to 500 ms for a central region of interest (ROI; electrodes FC1, FCz, FC2, C1, Cz, C2, CP1, CPz, and CP2), submitted to an ANOVA with repeated measures on factors electrode (9 levels), congruency (congruent, incongruent), task version, and suggestion. There were main effects of congruency, $F(1, 15) = 10.4$, $p < .01$, $\eta_p^2 = .41$, and electrode, $F(8, 120) = 6.7$, $p < .005$, $\varepsilon = .32$, $\eta_p^2 = .31$, and an interaction between suggestion and congruency, $F(1, 15) = 6.4$, $p < .05$, η_p^2

= .30. In addition, task version yielded a strong trend, $F(1, 15) = 4.5$, $p = .05$, $\eta_p^2 = .23$. Importantly, the congruency effect was not modulated by task version ($F < 1$).

Because the interaction between suggestion and congruency was significant, we analyzed the difference-waves between incongruent and congruent trials in the same time window and ROI and with the same factors (except for congruency). Results revealed a main effect of suggestion (M = -0.15 in NH, vs M = -0.20 in PHS), $F(1, 15) = 6.4$, $p < .05$, $\eta_p^2 = .30$, but no effect of task version ($F < 1$).

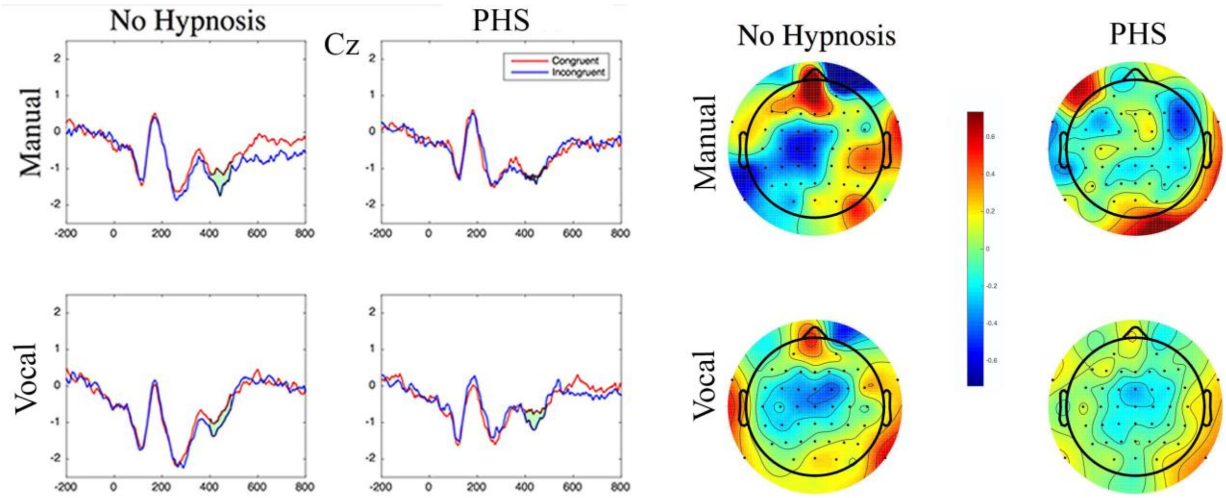


Figure 4. Left: Grand average ERPs at selected midline electrode (within the N400 time-window the differences between congruent and incongruent are highlighted by green shading). Right: Topographies of the difference between ERPs to incongruent and congruent conditions within the N400 time window of 420-500 ms (μV).

Response-locked ERPs. Finally, we calculated response-locked ERPs in order to check for conflicts in late response-related processes (Fig. 5). Mean amplitudes during the -200 to -50 ms pre-response interval were submitted to ANOVA with factors suggestion, task version, congruency (congruent vs. incongruent) and 10 electrodes in a posterior ROI (P5, P3, P1, Pz, P2, P4, P6, PO3, POz, PO4). There was a main effect of congruency, $F(1, 15) = 8.0$, $p < .05$, η_p^2

= .35, which interacted with task version, $F(1, 15) = 6.7$, $p < .05$, $\eta_p^2 = .31$, and with both suggestion and congruency, $F(9, 135) = 2.6$, $p < .05$, $\varepsilon = .75$, $\eta_p^2 = .15$. As can be seen in Figure 5a and 5b, the difference between congruent and incongruent trials is bigger for the vocal than for the manual task (M = -.28 vs. -.10 µV). When we separately checked the different task versions, the congruency effect failed significance in the manual task, $F(1, 15) = 2.4$, $p > .1$, $\eta_p^2 = .13$, but was highly significant in the vocal task, $F(1, 15) = 11.3$, $p < .01$, $\eta_p^2 = .43$.

In addition to a posterior focus, the left inferior frontal region in the vocal condition showed a congruency effect (Fig. 5b, bottom). ANOVA of mean amplitudes at electrodes F7, FT9, and T7 during a -220 to -120 pre-response time-window showed an interaction between task version and congruency, $F(1, 15) = 6.8$, $p < .05$, $\eta_p^2 = .31$. Separate post-hoc analyses at each task version revealed a main effect of congruency in the vocal task, $F(1, 15) = 5.3$, $p < .05$, $\eta_p^2 = .26$, but not in the manual task, $F(1, 15) = 1.6$, $p > .1$, $\eta_p^2 = .09$. Furthermore, in the vocal task, the interaction between congruency and suggestion was a strong trend, $F(1, 15) = 4.2$, $p = .05$, $\eta_p^2 = .21$.

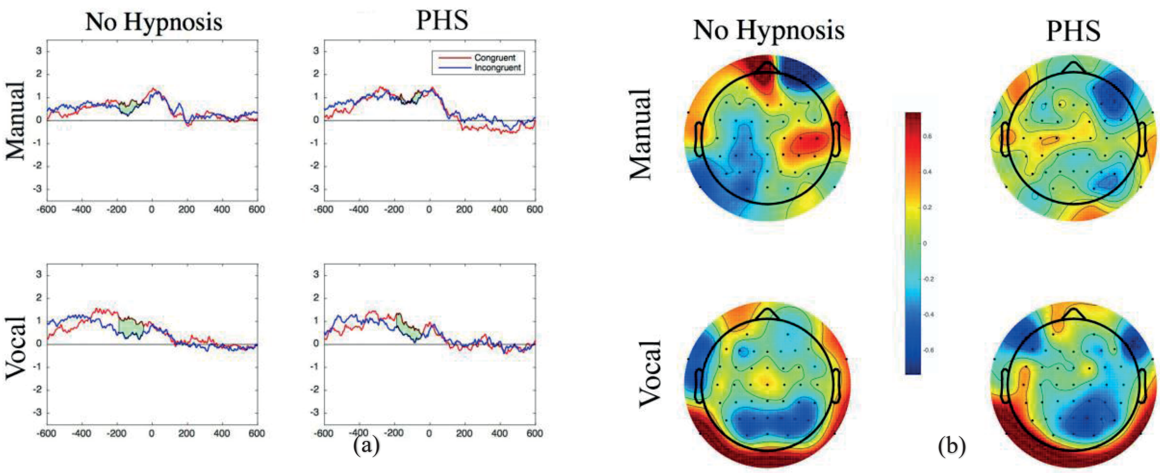


Figure 5. (a) Grand average response-locked ERPs over all electrodes in posterior ROI (the differences between congruent and incongruent, within the same time-window which is used for

topographies, are highlighted by green shading). (b) Topographies of difference-waves (incongruent minus congruent trials) for the -200 to -50 ms pre-response time-window.

Discussion

The main goal of the current study was to understand the nature of conflicts in two different, often-used versions of the Stroop task, the classic color naming task and the manual version, pressing buttons assigned to the print colors. We approached these aims by (1) manipulating the lexicality of the neutral trials, (2) impairing the processes of word reading by means of post-hypnotic suggestions (PHS), and (3) recording event-related potentials.

Comparing manual and vocal Stroop task versions

Not only the Stroop effect as a whole, but also its interference and facilitation components were appreciably and significantly bigger - almost double in size - in the vocal than in the manual Stroop task. This is in line with previous studies applying these versions of the Stroop task (Liotti et al., 2000; Redding & Gerjets, 1977). Also, in line with previous findings (e.g. Raz et al., 2006; Raz & Shapiro, 2002; Zahedi et al., 2017) PHS strongly diminished the Stroop effects in both task versions.

In order to explain the differential Stroop effects in the two task modalities, we may rule out - for a start - a locus at the lexical level, during reading. The lexicality variable employed for the neutral trials – albeit significant as a main effect – was comparable for the manual and vocal Stroop tasks (for similar findings in PWI suggesting that word frequency influences non-lexical stages, see Hutson et al., 2013). Therefore, there is no evidence for different loci of reading-related effects in the vocal and manual Stroop versions at the lexical level – in other words, the big difference in the Stroop effect between both task versions is unlikely to be due to differences in lexical layer activation during reading processes. Furthermore, the lexicality effect was not affected by PHS, which strongly attenuated both Stroop effects, indicating that the PHS effect does not originate from any lexical or pre-lexical source.

The absence of a differential lexicality effect for the two task versions is opposite to our hypothesis, that a major contributor to the differences between task versions would be lexicality effects. It should be noted that the (significant) nominal effect of lexicality was between 8 and 13 ms and, hence, does not seem to substantially contribute to the sizeable differences in the congruency effects of different task versions or PHS. In the section "Comparing Stroop and Picture Word Interference Tasks" we will further discuss why some other task formats, for example, PWI might yield larger lexicality effects; thus, the non-significant trend between strings of letters and low-frequency words that emerged in our results, might be stronger in the PWI than in the verbal Stroop task.

In order to explain the larger Stroop effect in the vocal as compared to the manual task version at least two suggestions can be made on the basis of the heuristic model presented in Figure 1. First, the semantic interaction in the vocal Stroop version may be more elaborated in both qualitative and quantitative terms than in the manual version. However, analysis of the N400 reflecting semantic effects did not reveal a clear dominance of the vocal over the manual version apart from a trend for a main effect of task version. Alternatively, the larger Stroop effect in the vocal version may be due to additional loci of interference and conflict between the two sources of information, that is, color processing and word recognition. In line with this idea, the response-locked ERPs revealed a discrepancy between the two task versions, indicating towards response-related conflicts in the vocal but not in the manual version. These additional loci of interference can be localized either in post-semantic layers, including the lexical and word form layers during word production, or in the articulatory buffer.

Interestingly, the left inferior-frontal and parietal scalp regions at which these conflicts were present (Fig. 5b bottom) include Broca's and Wernicke's areas, that have been related to phonological retrieval and syllabification (Indefrey, 2011). Intriguingly, the conflict component with parietal ERP distribution did not reveal any modulation by post-hypnotic suggestions, whereas the conflict with left inferior-frontal manifestation showed a strong trend towards a mitigation by hypnosis. This might indicate that PHS reduce conflicts in the language production layer in the vocal Stroop task version. Hence, these results are in line with the idea that as compared to the manual task there is at least one additional locus of conflict in the vocal task during word production, enhancing the Stroop effect.

Post-hypnotic suggestions aiming at “agnosia” (words losing their meaning) decreased the interference component in RTs by about 60 ms in the vocal and by 40 ms in the manual version; in contrast, the facilitation component was reduced to a similar extent in both task versions (24 vs. 20 ms). Hence, PHS modulated the interference and facilitation effects differently in the two task versions. These results allow a more specific interpretation of the differential loci.

The heuristic model in Figure 1 suggests a common locus of interaction between the information derived from print color and word meaning at the semantic representation layer for both task versions, where both facilitation and interference should occur. For the vocal task the model also suggests a locus of interaction at the response production layer (articulatory buffer), which consists of interference between competing responses but does not involve facilitation, as the buffer must be cleared out from the occupying word before the next word can enter. The model suggests also a response-related locus of the interaction in the manual task, which should consist of both facilitation and interference between the responses activated by print color and word meaning. Importantly, the response-related interactions should differ between vocal and manual Stroop versions.

We argue that besides the shared loci (see discussion below) there are also differential loci involved in vocal and manual task versions because (1) PHS diminish the interference component in RT more strongly in the vocal than in the manual task. This is in line with the idea that "agnosia" for word meaning will reduce conflicts not only at the semantic but also on the articulatory level. (2) In response-locked ERPs we found a significant Stroop effect only for the vocal condition, which in turn was diminished by post-hypnotic suggestions. Hence the results support a locus of interference that is specific for the vocal task version and resides at the response level (Mahon et al., 2007). In contrast to these findings, when manual tasks involve lexical access (e.g., attributes of the names are classified manually), semantic interference effects have been reported that are indistinguishable from those observed in tasks that include overt speech production, suggesting similar lexico-semantic loci that do not depend on the involvement of an articulatory stage (Abdel Rahman & Aristei, 2012).

However, at least one of our findings requires a further clarification or modification of the suggested models. The facilitation component in RTs is much stronger in the vocal than in the manual task. Based on our previous interpretation that greater interference in the vocal Stroop version is due to an additional locus of interference in the articulatory layer, the interaction between two pathways in this layer cannot be facilitatory, because the output buffer is a single channel and can only accept one response as final output: in short, we cannot articulate two words at the same time. Therefore, based on the proposed model, the facilitation should be caused by something else than additional loci of interference. One may argue that the greater facilitation in the vocal task is due to stronger semantic interaction; however, the Stroop effect on the N400 is not different between tasks. If anything, it tends to be a bit weaker in the vocal version, arguing for similar semantic conflicts in both tasks. There are at least two accounts for these findings: (1) the semantic conflict in the vocal version might be larger than in the manual version and we should discard the N400 effects, for example, because of their somewhat non-standard scalp distribution. This would beg the question what the N400 effects would signify. (2) The stronger facilitation in the vocal task might be due to an additional conflict in one of the shared loci of interaction between two tasks, but with a different time-course from what we expect from N400. Assuming that lexical and word form layers will be activated first during reading, and then additionally during word production, there will be repeated or cumulative activation in these layers, which may result in additional semantic-lexical and/or word form effects during word production. Consequently, we suggest that backpropagation of activation from the semantic to the lexical or from the lexical to the word form layer may cause this greater facilitation (and, where applicable, additional interference as well), rather than forward propagation from the letter perception to the lexical layer or from the lexical to the semantic layer. These effects would follow the first pass processing and might, therefore, be too late to affect the N400 component. It is conceivable that the parietal components in the response-synchronized ERP for the vocal task reflects this renewed congruency effect due to the backpropagations. This late (parietal) congruency effect was not affected by PHS, which may suggest that as processing had moved on to the next layer these interferences and facilitation could not be reduced with employing additional executive resources.

Additionally, one may assert that the stronger effects in the vocal Stroop version are due to a longer word production segment as compared to the manual version. However, the fact that in the vocal task, RTs in response to neutral trials was comparable to RTs in response to neutral trials in the manual task, is not in line with this hypothesis, and indicates that in both versions default RTs in response to neutral categories are comparable.

Taken together, we argue that the differences in the Stroop effects in the vocal and manual versions are not related to the differential employment of lexical or pre-lexical levels during word reading. We suggest that at a semantic level first pass congruency effects are similar. The stronger behavioral Stroop effect in the vocal version seems to be due to two specific sources: (1) additional interference in the articulatory layer and (2) stronger lexical and post-lexical activation during language production. In addition, back propagation from lexical and post-lexical layers activated during word production to the semantic layer might cause further semantic interference. Also, the idea that Stroop effects in both the manual and the vocal version involve semantic-lexical interference conforms with a recent computational model by Kalanthroff et al. (2018).

Effects of Post-Hypnotic Suggestions

In the analysis discussed above, PHS have shown to be a useful tool to interpret the differences between the vocal and manual Stroop effect. However, the present study also offers the chance to elucidate the locus of PHS of “agnosia” on Stroop interference. To this aim, let’s first consider the lexicality effect in the neutral trials. Although the Stroop effect was diminished strongly in the presence of the post-hypnotic suggestion that words “had lost their meaning”, the lexicality effects in RTs did not significantly change. Although the lexicality effect was small, it was numerically somewhat bigger after PHS. Hence, the absence of a significant PHS effect is not due to insufficient power. This is an indication that the present PHS do not affect lexical or pre-lexical word processing segment, but affect only post-lexical stages.

With respect to ERPs and PHS three points shall be discussed. First, in presence of PHS there was a condition-general increase in an early frontally distributed N1 component, followed by a general reduction in the N2 component with a central-posterior maximum. These findings are in line with our previous report on changes in increased theta power in EEG induced by PHS (Zahedi et al., 2017) indicating that cognitive control is proactively recruited in all trial types to a similar extent. According to the increased N1 amplitude, initial deployment of cognitive control acts very fast and may have decreases the load on later processes, for example, as reflected in the N2 component, often seen as related to performance monitoring and conflict control. Intriguingly, our results are comparable to those of Coderre and van Heuven (2014), who explored differences between bilingual and monolingual participants in regard to Stroop performance, and found similar differences in similar time window as in our analysis. Coderre et al. (2011) suggested that enhanced executive functions in bilingual participants allow better inhibition of irrelevant word meaning. Recently, Lehtonen et al. (2018) argued that the differences between bilingual and monolingual participants in cognitive tasks involving language production pathways may be due to differential language exposure rather than advantages in cognitive control. Therefore, the resemblance between our results and effects of bilingualism may also indicate a decrease in the prepotency of reading habits due to PHS. Further, Scharinger et al. (2017) found a modulation of the N1 by congruency in the Stroop task in older but not younger participants; importantly, performance quality was positively related with bigger N1 amplitudes.

Second, we investigated differences in P3 amplitudes. It is important to consider that the P3 was the earliest component showing congruency effects, but only as a difference between neutral versus both congruent as well as incongruent trials, which, therefore, cannot be related to interference or facilitation. As the P3 effects in the present data concern a P3b-like component with parietal topography, they may reflect the allocation of motivated attention (Polich, 2007; van Dinteren et al., 2014). From this perspective, the recruitment of executive functions helps to steer cognitive and attentional resources more diligently and meticulously in response to both congruent and incongruent trials (i.e. color words), where the possibility of interaction is greater. Coherently, we have found a bigger difference between neutral and congruent trials in presence of PHS, indicating that the PHS enhance executive functions, and as a consequence improve performance.

Third, in the absence of PHS, we found an N400 effect between incongruent and congruent conditions, similar as in previous studies both with respect to topographies, amplitude and latency (Hanslmayr et al., 2008; Ilan & Polich, 1999; Liotti et al., 2000; West & Alain, 1999). However, after PHS, the N400 effect was attenuated. Given the fact that this component is related to semantic-processing, this was expected and shows that semantic word processing is diminished by PHS.

To summarize, ERP findings related to PHS suggest an early recruitment of cognitive control, in all conditions (as the increase in N1 suggests), resulting in the reduced necessity for conflict detection (as the decrease in N2 indicates). Further, enhanced attentional allocation to both congruent and incongruent color words but not to neutral non-color words reflected in the P3 is followed by a smaller N400 effects of compatibility, an interference-related component. Therefore, PHS act on a cascade of processes all directed on enhancing cognitive control and diminishing interference.

In regards to our interpretation of N1 and N2, we suggest that PHS enhanced proactive control, allocated regardless of the specific congruency condition, or even existence of the conflict. Actually, proactive control is recruited in situations where there might be conflict, whether or not a given trial actually does involve any conflict (Belanger et al., 2010; Braver, 2012; Braver & West, 2008). This allocation of control was supposedly reflected in bigger N1 amplitudes but smaller N2, regardless of congruency. Therefore, the recruitment of more proactive control in advance of the trial helps to deal with conflicts, in case that they arise. However, handling of the actual conflict is reflected only in later components and not in these earlier components. If PHS had indeed affected reactive control instead, where the nature of the trial determines the amount of invested control, we should have observed an interaction of congruency and PHS, which was not the case.

However, one might ask about the bigger congruency effects in P3 component under influence of PHS versus no-hypnosis? It is remarkable that in the P3 component as well, the congruent and incongruent trials did not differ, and the preexisting difference between neutral and congruent-incongruent categories were amplified under effects of PHS versus NH condition. Consequently, still the recruited additional cognitive control under PHS, in our interpretation, is closer to proactive rather than reactive control.

Comparing Stroop and Picture Word Interference Tasks

The Stroop task and Stroop-like tasks such as PWI can be viewed as variants of the same or at least strongly related tasks (MacLeod, 1991; Starreveld & La Heij, 2017; van Maanen et al., 2009). Overall, Stroop effects were bigger in the vocal compared to the manual task. However, there was no difference in the lexicality effect between the two versions. It has to be considered, however, that the frequency and lexicality effects observed in our study were small as compared to what usually has been observed in PWI (Dhooge & Hartsuiker, 2010, 2011; Geng et al., 2013; Miozzo & Caramazza, 2003). In both of the Stroop and PWI task, combinations of visual information (objects or colors) and simultaneously presented words are shown; while the word is to be ignored, a response to the visual information is to be given. One of the differences between the Stroop and PWI tasks relates to the comparisons between congruent, incongruent and neutral conditions, another, presumably more crucial, difference relates to the number of different stimuli and categories used. In the classic Stroop task, only a few color words are repeatedly presented, whereas in the PWI task many different objects from different categories are presented, and may be presented only once. When these differences are minimized, both tasks are associated with similar effects, suggesting shared or overlapping mechanisms (e.g. Shitova et al., 2016). The study by Geng et al. (2013) shows that the inherent differences between Stroop and PWI tasks affect the speed of processing the targets. This, in turn, has an impact on word frequency effects. Geng et al. (2013) suggested that the faster processing of targets in Stroop task renders the distractor words ineffective, as they are processed only after the targets.

Revisiting the Stroop Model

In accordance to the model, we found first, stronger effects in RT performance – almost double in size in vocal task in comparison to the manual task – revealing at least a quantitative difference between task versions. Second, the difference between incongruent and congruent trials in response-locked ERPs was significant in the vocal, but not in manual task, and these differences were recorded over Broca's and Wernicke's area, relating to language production and word form retrieval. Finally, the fact that Stroop effects and their interference components, but not their facilitation components, were differently reduced in the vocal version by PHS, further corroborate to existence of different loci of interaction in two task modalities.

One may argue that the effects were exclusively due to the interaction between two paths (i.e. word recognition and color perception) in the articulators (Mahon et al., 2007). However, the effects were present in the manual version, too, and highly similar to the vocal task. In that sense, we argue, this theory in itself cannot predict or explain these similarities (because, although the response production segments are different between two tasks, but there are appreciable similarities between their effects in regard to N1, N2, P3 and N400).

Limitations and Perspectives

It is important to consider that in the present experiment the Stroop effects after the PHS were reduced only moderately as compared to our own previous study (Zahedi et al., 2017), and some others (Raz et al., 2005; Raz et al., 2003; Raz & Shapiro, 2002). Raz et al. (2007) tested a larger participant sample than the previously mentioned studies (e.g. Raz et al., 2005; Raz et al., 2003; Raz & Shapiro, 2002; Zahedi et al., 2017) and showed a similarly moderate reduction of the Stroop effect as in the present study. Further, it has to be considered that we used a longer-version of the Stroop task with 640 trials, which lasted about an hour to be administrated completely. Zahedi et al. (2017) ascribed the effects of post-hypnotic suggestions to be based on executive functions. Following this argument, the moderate reduction of the Stroop effect in the present study can be attributed to lassitude and fatigue, that is, PHS may wear down over a longer period of time. This idea, however, needs further study.

Also it is noticeable, the induction of hypnosis in the PHS session increased the duration of the latter as compared to the no-hypnosis session by one hour. However, based on our previous study (Zahedi, Stuermer, Hatami, Rostami, & Sommer, 2017), where the effect of hypnosis alone and hypnosis plus PHS were compared with a no-hypnosis condition, we do not think that this delay has affected the results to a great extent because in that study we did not find any difference between hypnosis alone and no-hypnosis in regards to EEG oscillations nor Stroop task performance.

Despite some theoretically important differences both stimulus- and response-locked ERPs recorded in the manual and vocal Stroop task versions were surprisingly similar in terms of waveforms, topographies and statistical analyses. We consider this result as a further validation of the applied articulation artifact rejection method (Ouyang et al., 2016). This is encouraging for applying RIDE in further studies with overt articulation.

We would like to point out that we did not include strings of letters in our neutral categories (e.g. *LLLL* or *XXXX*), but instead used pseudo-words (scrambled words). The reasons were two-fold. First, because in our experiment, we wanted to focus on the interactions of the word reading pathway with the color perception pathway, and to assess the effects of PHSs on these pathways, we preferred pseudo-words over strings of letters or color patches. And second, based on a debate in the literature about the importance of integrating two pathways involved in Stroop tasks, for example, color perception and word reading (for review see MacLeod, 1991), strings of letters would not constitute an appropriate neutral baseline for comparing different task versions. Neither letter strings nor color patches would involve the word processing pathway as words or pseudo-words do and, because of their distinctiveness from words and pseudo-words, they would be unlikely to enter the word processing pathway. Consequently, also any conflicts between strings of letters and congruent trials, "task conflicts" as termed by some authors (Goldfarb & Henik, 2007; Kalanthroff et al., 2018), were not addressed in our study.

It is noteworthy, that in the current study, 192 of the 320 trials in total (i.e., 60%), were neutral. This scarcity of target words might have increased the congruency effect, relative to a more common situation with a higher proportion of target words (Tzelgov et al., 1992). In our previous study (Zahedi et al., 2017), in a manual Stroop task, with 33 % neutral trials, we found 42 and 52 ms interference, for no-hypnosis and hypnosis without PHS conditions respectively.

These smaller effects in comparison to the 70 ms interference in the manual version of the present study, can be interpreted as a trend in the predicted direction. However, let us point out, that effects are comparable in size and if anything, more pronounced in the present study. Most importantly, we do not see any reason, why the higher proportion of neutral trials in both task versions should have affected their specific mechanisms.

Finally, in the analysis of the N400 component, we were not able to include the neutral categories, mainly due to the big residual of the P3 component overlapping with the N400 (see Figs. 2b and 3a). This differential overlap of the late positivity in the time-window of the N400 component, i.e. 420 to 500 ms, renders any interpretation of the difference of the neutral and the target conditions highly ambiguous. However, the N400 component, that is the difference on congruent versus incongruent conditions (e.g. Hirschfeld et al., 2008; Liotti et al., 2000), remains interpretable because these conditions maximize effects of semantic/lexical processing, unconfounded by stimulus probability.

Conclusions

The present study focused on cognitive control, a set of multi-purpose functions invoked when prepotent behavior is insufficient to handle a situation. Cognitive control is directly or indirectly relevant for many areas of experimental psychology, for example, memory, especially short-term memory, executive functions, self- regulation (such as food intake or impulsivity control) and its development, and decision making. Here we employed the Stroop task as a frequently used experimental paradigm challenging the inhibition function. Most importantly, we addressed the long-standing question how the classic vocal version of the Stroop task, requiring color naming, and its manual version, requiring pressing color-labeled buttons, differ in terms of their loci of the interference that has to be resolved. As one of our research tools, we applied post-hypnotic suggestions aiming at the likely source of interference, that is word reading. Hypnosis, which has gained scientific momentum in recent years, strongly diminished the Stroop effect in both task versions to a similar degree. Our second tool was the analysis of specific ERP components that allow time-resolved insights into the cognitive sub-processes employed in a task. Hitherto, the investigation of ERPs in the vocal Stroop task has been hampered by the massive articulation artifact occluding the late ERP components. Here we employed a new technique for ERP analysis that allows eliminating these artifacts to uncover both common and specific loci of interference in the two Stroop task versions. The ERP technique revealed that the control over the Stroop interference by PHS is largely proactive by allocating relevant resources as early as 100 ms after stimulus presentation.

Together, our behavioral and ERPs findings indicate that the manual and vocal Stroop task versions share a common locus of interaction during semantic activation. However, for the vocal task, a further locus of interaction close to articulation exists, which is absent in the manual version. Our findings revealed a post-lexical locus of the effects of post-hypnotic suggestions that can be attributed to a cascade of enhanced proactive control processes.

The present study has therefore contributed to specific questions about the Stroop effect that are of interest for the study of executive control in general and also language research. Moreover, the present study may serve as an example of how the combination of PHS and the employment of advanced methods in ERP analysis may aid in resolving open questions of cognitive psychology and psycholinguistics.

Context of the Research

This study as a part of the doctoral thesis of Anoushiravan Zahedi, the first author of the manuscript, following up on his master's thesis, "Eliminating Stroop effects with post-hypnotic instructions”, conducted at the University of Tehran under the supervision of Javad Hatami and Werner Sommer (Zahedi et al., 2017). In the present study, conducted in Berlin, we further scrutinized the nature of PHS on two classic versions of the Stroop task, manual and vocal. To this aim, we collaborated with Rasha Abdel Rahman, who has long-standing experience in the study of language production with ERPs, which in many ways overlaps with the vocal Stroop task. Birgit Stürmer joined the team to bring in her vast knowledge about ERP research on cognitive control. Together we aimed at investigating how inhibition processes of cognitive control are involved in different Stroop task versions. This was greatly facilitated by a recent methodological development in eliminating articulation artifacts in the ERP in which both Werner Sommer and Rasha Abdel Rahman had been involved. This new method allowed – for the first time – to directly compare the mechanisms underlying the Stroop conflicts in the two task versions (reflected in long-latency ERP components) and their modulation by PHS. Ongoing studies aim to extend the application of PHS to other executive functions in order to address the question of their unity or diversity.

References

Abdel Rahman, R., & Aristei, S. (2010). Now you see it ... and now again: semantic interference reflects lexical competition in speech production with and without articulation. *Psychonmic Bulletin and Review*, *17*(5), 657-661. https://doi.org/10.3758/PBR.17.5.657

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes1. In *Psychology of learning and motivation* (Vol. 2, pp. 89-195). Elsevier.

Baddeley, A. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology*, *49*(1), 5-28. <Go to ISI>://WOS:A1996UF60400002

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, *4*(10), 829-839. https://doi.org/10.1038/nrn1201

Baddeley, A., & Hitch, G. (1974). Working Memory. *8*, 47-89. https://doi.org/10.1016/s0079-7421(08)60452-1

Badzakova-Trajkov, G., Barnett, K. J., Waldie, K. E., & Kirk, I. J. (2009). An ERP investigation of the Stroop task: the role of the cingulate in attentional allocation and conflict resolution. *Brain Research*, *1253*, 139-148. https://doi.org/10.1016/j.brainres.2008.11.069

Banich, M. T., Milham, M. P., Atchley, R., Cohen, N. J., Webb, A., Wszalek, T., Kramer, A. F., Liang, Z. P., Wright, A., Shenker, J., & Magin, R. (2000). fMri studies of Stroop tasks reveal unique roles of anterior and posterior brain systems in attentional selection. *Journal of Cognitive Neuroscience*, *12*(6), 988-1000. https://www.ncbi.nlm.nih.gov/pubmed/11177419

Belanger, S., Belleville, S., & Gauthier, S. (2010). Inhibition impairments in Alzheimer's disease, mild cognitive impairment and healthy aging: effect of congruency proportion in a Stroop task. *Neuropsychologia*, *48*(2), 581-590. https://doi.org/10.1016/j.neuropsychologia.2009.10.021

Bongartz, W. (1985). German norms for the Harvard Group Scale of Hypnotic Susceptibility, Form A. *International Journal Of Clinical & Experimental Hypnosis*, *33*(2), 131-139. https://doi.org/10.1080/00207148508406643

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624-652. https://doi.org/10.1037/0033-295X.108.3.624

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms framework. *Trends in cognitive sciences*, *16*(2), 106-113. https://doi.org/10.1016/j.tics.2011.12.010

Braver, T. S., & West, R. (2008). Working memory, executive control, and aging. *The handbook of aging and cognition*, *3*, 311-372.

Bub, D. N., Masson, M. E., & Lalonde, C. E. (2006). Cognitive control in children: stroop interference and suppression of word reading. *Psychol Sci*, *17*(4), 351-357. https://doi.org/10.1111/j.1467-9280.2006.01710.x

Burt, J. S., & Tate, H. (2002). Does a reading lexicon provide orthographic representations for spelling? *Journal of Memory and Language*, *46*(3), 518-543. https://doi.org/10.1006/jmla.2001.2818

Catling, J. C., Dent, K., Johnston, R. A., & Balding, R. (2010). Age of acquisition, word frequency, and picture-word interference. *Quarterly Journal of Experimental Psychology*, *63*(7), 1304-1317. https://doi.org/10.1080/17470210903380830

Coderre, E., Conklin, K., & van Heuven, W. J. (2011). Electrophysiological measures of conflict detection and resolution in the Stroop task. *Brain Research*, *1413*, 51-59. https://doi.org/10.1016/j.brainres.2011.07.017

Coderre, E., & van Heuven, W. J. (2014). Electrophysiological explorations of the bilingual advantage: evidence from a Stroop task. *Plos One*, *9*(7), e103424. https://doi.org/10.1371/journal.pone.0103424

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychological Review*, *97*(3), 332-361. https://doi.org/10.1037/0033-295X.97.3.332

Coles, M. G. (1989). Modern mind-brain reading: psychophysiology, physiology, and cognition. *Psychophysiology*, *26*(3), 251-269. https://www.ncbi.nlm.nih.gov/pubmed/2667018

Collette, F., Van der Linden, M., Laureys, S., Delfiore, G., Degueldre, C., Luxen, A., & Salmon, E. (2005). Exploring the unity and diversity of the neural substrates of executive functioning. *Human Brain Mapping*, *25*(4), 409-423. https://doi.org/10.1002/hbm.20118

Costa, A., Strijkers, K., Martin, C., & Thierry, G. (2009). The time course of word retrieval revealed by event-related brain potentials during overt speech. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(50), 21442-21446. https://doi.org/10.1073/pnas.0908921106

Dell'acqua, R., Sessa, P., Peressotti, F., Mulatti, C., Navarrete, E., & Grainger, J. (2010). ERP evidence for ultra-fast semantic processing in the picture-word interference paradigm. *Front Psychol*, *1*, 177. https://doi.org/10.3389/fpsyg.2010.00177

Dell, G. S. (1986). A spreading-activation theory of retrieval in sentence production. *Psychology Review*, *93*(3), 283-321. https://www.ncbi.nlm.nih.gov/pubmed/3749399

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J Neurosci Methods*, *134*(1), 9-21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dhooge, E., & Hartsuiker, R. J. (2010). The distractor frequency effect in picture-word interference: Evidence for response exclusion. *J Exp Psychol Learn Mem Cogn*, *36*(4), 878-891. https://doi.org/10.1037/a0019128

Dhooge, E., & Hartsuiker, R. J. (2011). The distractor frequency effect in a delayed picture-word interference task: further evidence for a late locus of distractor exclusion. *Psychon Bull Rev*, *18*(1), 116-122. https://doi.org/10.3758/s13423-010-0026-0

Diamond, A. (2013). Executive functions. *Annu Rev Psychol*, *64*, 135-168. https://doi.org/10.1146/annurev-psych-113011-143750

Diamond, A., & Ling, D. S. (2016). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Dev Cogn Neurosci*, *18*, 34-48. https://doi.org/10.1016/j.dcn.2015.11.005

Dickman, S. J. (1990). Functional and dysfunctional impulsivity: personality and cognitive correlates. *J Pers Soc Psychol*, *58*(1), 95-102. https://www.ncbi.nlm.nih.gov/pubmed/2308076

Dohle, S., Diel, K., & Hofmann, W. (2018). Executive functions and the self-regulation of eating behavior: A review. *Appetite*, *124*, 4-9. https://doi.org/10.1016/j.appet.2017.05.041

Elkins, G. R., Barabasz, A. F., Council, J. R., & Spiegel, D. (2015). Advancing research and practice: The revised APA Division 30 definition of hypnosis. *Am J Clin Hypn*, *57*(4), 378-385. https://doi.org/10.1080/00029157.2015.1011465

Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: a review. *Psychophysiology*, *45*(1), 152-170. https://doi.org/10.1111/j.1469-8986.2007.00602.x
Geng, J., Schnur, T. T., & Janssen, N. (2013). Relative speed of processing affects interference in Stroop and picture–word interference paradigms: evidence from the distractor frequency effect. *Language, Cognition and Neuroscience*, *29*(9), 1100-1114. https://doi.org/10.1080/01690965.2013.846473
Geyken, A. (2007). The DWDS corpus: A reference corpus for the German language of the 20th century. *Collocations and Idioms: Linguistic, lexicographic, and computational aspects*, 23-41.
Glaser, W. R., & Glaser, M. O. (1989). Context effects in stroop-like word and picture processing. *Journal of Experimental Psychology: General*, *118*(1).
Goldfarb, L., & Henik, A. (2007). Evidence for task conflict in the Stroop effect. *J Exp Psychol Hum Percept Perform*, *33*(5), 1170-1176. https://doi.org/10.1037/0096-1523.33.5.1170
Guerrieri, R., Nederkoorn, C., & Jansen, A. (2008). The interaction between impulsivity and a varied food environment: its influence on food intake and overweight. *Int J Obes (Lond)*, *32*(4), 708-714. https://doi.org/10.1038/sj.ijo.0803770
Hammond, D. C. (1990). *Handbook of hypnotic suggestions and metaphors*. WW Norton & Company.
Hammond, D. C. (1998). *Hypnotic induction and suggestion*. American Society of Clinical Hypnosis.
Hanslmayr, S., Pastotter, B., Bauml, K. H., Gruber, S., Wimber, M., & Klimesch, W. (2008). The electrophysiological dynamics of interference during the Stroop task. *J Cogn Neurosci*, *20*(2), 215-225. https://doi.org/10.1162/jocn.2008.20020
Hirschfeld, G., Jansma, B., Bolte, J., & Zwitserlood, P. (2008). Interference and facilitation in overt speech production investigated with event-related potentials. *Neuroreport*, *19*(12), 1227-1230. https://doi.org/10.1097/WNR.0b013e328309ecd1
Hock, H. S., & Egeth, H. (1970). Verbal interference with encoding in a perceptual classification task. *J Exp Psychol*, *83*(2), 299-303. https://www.ncbi.nlm.nih.gov/pubmed/5480902
Hutson, J., Damian, M. F., & Spalek, K. (2013). Distractor frequency effects in picture–word interference tasks with vocal and manual responses. *Language and Cognitive Processes*, *28*(5), 615-632. https://doi.org/10.1080/01690965.2011.605599
Ilan, A. B., & Polich, J. (1999). P300 and response time from a manual Stroop task. *Clin Neurophysiol*, *110*(2), 367-373. https://www.ncbi.nlm.nih.gov/pubmed/10210626
Indefrey, P. (2011). The spatial and temporal signatures of word production components: a critical update. *Front Psychol*, *2*, 255. https://doi.org/10.3389/fpsyg.2011.00255
Ishihara, S. (1996). *Ishihara's tests for colour-deficiency*. Kanehara & Company.
Jensen, M. P., Jamieson, G. A., Lutz, A., Mazzoni, G., McGeown, W. J., Santarcangelo, E. L., Demertzi, A., De Pascalis, V., Banyai, E. I., Rominger, C., Vuilleumier, P., Faymonville, M. E., & Terhune, D. B. (2017). New directions in hypnosis research: strategies for advancing the cognitive and clinical neuroscience of hypnosis. *Neurosci Conscious*, *3*(1). https://doi.org/10.1093/nc/nix004
Kalanthroff, E., Davelaar, E. J., Henik, A., Goldfarb, L., & Usher, M. (2018). Task conflict and proactive control: A computational theory of the Stroop task. *Psychological Review*, *125*(1), 59-82. https://doi.org/10.1037/rev0000083

Kornblum, S. (1994). The way irrelevant dimensions are processed depends on what they overlap with: The case of Stroop-and Simon-like stimuli. *Psychological Research-Psychologische Forschung*, *56*(3), 130-135. https://doi.org/Doi 10.1007/Bf00419699

Langenecker, S. A., Nielson, K. A., & Rao, S. M. (2004). fMRI of healthy older adults during Stroop interference. *Neuroimage*, *21*(1), 192-200. https://doi.org/10.1016/j.neuroimage.2003.08.027

Lehtonen, M., Soveri, A., Laine, A., Jarvenpaa, J., de Bruin, A., & Antfolk, J. (2018). Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychol Bull*, *144*(4), 394-425. https://doi.org/10.1037/bul0000142

Levelt, W. J. (1999). Models of word production. *Trends Cogn Sci*, *3*(6), 223-232. https://www.ncbi.nlm.nih.gov/pubmed/10354575

Levelt, W. J., Roelofs, A., & Meyer, A. S. (1999). Multiple perspectives on word production. *Behavioral and Brain Sciences*, *22*(1), 61-69. https://doi.org/10.1017/s0140525x99451775

Levelt, W. J. M., Schriefers, H., Vorberg, D., Meyer, A. S., Pechmann, T., & Havinga, J. (1991). The Time Course of Lexical Access in Speech Production - a Study of Picture Naming. *Psychological Review*, *98*(1), 122-142. https://doi.org/Doi 10.1037//0033-295x.98.1.122

Lifshitz, M., Aubert Bonn, N., Fischer, A., Kashem, I. F., & Raz, A. (2013). Using suggestion to modulate automatic processes: from Stroop to McGurk and beyond. *Cortex*, *49*(2), 463-473. https://doi.org/10.1016/j.cortex.2012.08.007

Liotti, M., Woldorff, M. G., Perez, R., & Mayberg, H. S. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia*, *38*(5), 701-711. https://www.ncbi.nlm.nih.gov/pubmed/10689046

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: an integrative review. *Psychol Bull*, *109*(2), 163-203. https://doi.org/10.1037/0033-2909.109.2.163

Maess, B., Friederici, A. D., Damian, M., Meyer, A. S., & Levelt, W. J. (2002). Semantic category interference in overt picture naming: sharpening current density localization by PCA. *J Cogn Neurosci*, *14*(3), 455-462. https://doi.org/10.1162/089892902317361967

Mahon, B. Z., Costa, A., Peterson, R., Vargas, K. A., & Caramazza, A. (2007). Lexical selection is not by competition: a reinterpretation of semantic interference and facilitation effects in the picture-word interference paradigm. *J Exp Psychol Learn Mem Cogn*, *33*(3), 503-535. https://doi.org/10.1037/0278-7393.33.3.503

Milham, M. P., Banich, M. T., & Barad, V. (2003). Competition for priority in processing increases prefrontal cortex's involvement in top-down control: an event-related fMRI study of the stroop task. *Cognitive Brain Research*, *17*(2), 212-222. https://doi.org/10.1016/s0926-6410(03)00108-3

Miozzo, M., & Caramazza, A. (2003). When more is less: A counterintuitive effect of distractor frequency in the picture-word interference paradigm. *Journal of Experimental Psychology: General*, *132*(2), 228-252. https://doi.org/10.1037/0096-3445.132.2.228

Miyake, A., & Friedman, N. P. (2012). The Nature and Organization of Individual Differences in Executive Functions: Four General Conclusions. *Curr Dir Psychol Sci*, *21*(1), 8-14. https://doi.org/10.1177/0963721411429458

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cogn Psychol*, *41*(1), 49-100. https://doi.org/10.1006/cogp.1999.0734

Nash, M. R. (2005). The importance of being earnest when crafting definitions: science and scientism are not the same thing. *Int J Clin Exp Hypn*, *53*(3), 265-280. https://doi.org/10.1080/00207140590961934

Nederkoorn, C., Guerrieri, R., Havermans, R. C., Roefs, A., & Jansen, A. (2009). The interactive effect of hunger and impulsivity on food intake and purchase in a virtual supermarket. *Int J Obes (Lond)*, *33*(8), 905-912. https://doi.org/10.1038/ijo.2009.98

Nederkoorn, C., Houben, K., Hofmann, W., Roefs, A., & Jansen, A. (2010). Control yourself or just eat what you like? Weight gain over a year is predicted by an interactive effect of response inhibition and implicit preference for snack foods. *Health Psychology*, *29*(4), 389-393. https://doi.org/10.1037/a0019921

Niendam, T. A., Laird, A. R., Ray, K. L., Dean, Y. M., Glahn, D. C., & Carter, C. S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cogn Affect Behav Neurosci*, *12*(2), 241-268. https://doi.org/10.3758/s13415-011-0083-5

Ouyang, G., Schacht, A., Zhou, C., & Sommer, W. (2013). Overcoming limitations of the ERP method with Residue Iteration Decomposition (RIDE): a demonstration in go/no-go experiments. *Psychophysiology*, *50*(3), 253-265. https://doi.org/10.1111/psyp.12004

Ouyang, G., Sommer, W., Zhou, C., Aristei, S., Pinkpank, T., & Abdel Rahman, R. (2016). Articulation artifacts during overt language production in event-related brain potentials: Description and correction. *Brain Topogr*, *29*(6), 791-813. https://doi.org/10.1007/s10548-016-0515-1

Pardo, J. V., Pardo, P. J., Janer, K. W., & Raichle, M. E. (1990). The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. *Proc Natl Acad Sci U S A*, *87*(1), 256-259. https://www.ncbi.nlm.nih.gov/pubmed/2296583

Peterson, B. S., Skudlarski, P., Gatenby, J. C., Zhang, H., Anderson, A. W., & Gore, J. C. (1999). An fMRI study of Stroop word-color interference: evidence for cingulate subregions subserving multiple distributed attentional systems. *Biol Psychiatry*, *45*(10), 1237-1258. https://www.ncbi.nlm.nih.gov/pubmed/10349031

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clin Neurophysiol*, *118*(10), 2128-2148. https://doi.org/10.1016/j.clinph.2007.04.019

Raz, A., Fan, J., & Posner, M. I. (2005). Hypnotic suggestion reduces conflict in the human brain. *Proc Natl Acad Sci U S A*, *102*(28), 9978-9983. https://doi.org/10.1073/pnas.0503064102

Raz, A., Kirsch, I., Pollard, J., & Nitkin-Kaner, Y. (2006). Suggestion reduces the stroop effect. *Psychol Sci*, *17*(2), 91-95. https://doi.org/10.1111/j.1467-9280.2006.01669.x

Raz, A., Landzberg, K. S., Schweizer, H. R., Zephrani, Z. R., Shapiro, T., Fan, J., & Posner, M. I. (2003). Posthypnotic suggestion and the modulation of Stroop interference under cycloplegia. *Conscious Cogn*, *12*(3), 332-346. https://doi.org/10.1016/s1053-8100(03)00024-2

Raz, A., Moreno-Iniguez, M., Martin, L., & Zhu, H. (2007). Suggestion overrides the Stroop effect in highly hypnotizable individuals. *Conscious Cogn*, *16*(2), 331-338. https://doi.org/10.1016/j.concog.2006.04.004

Raz, A., & Shapiro, T. (2002). Hypnosis and neuroscience: a cross talk between clinical and cognitive research. *Arch Gen Psychiatry*, *59*(1), 85-90. https://doi.org/10.1001/archpsyc.59.1.85

Redding, G. M., & Gerjets, D. A. (1977). Stroop effect: interference and facilitation with verbal and manual responses. *Percept Mot Skills*, *45*(1), 11-17. https://doi.org/10.2466/pms.1977.45.1.11

Rose, S. B., & Abdel Rahman, R. (2016). Semantic similarity promotes interference in the continuous naming paradigm: behavioural and electrophysiological evidence. *Language, Cognition and Neuroscience*, *32*(1), 55-68. https://doi.org/10.1080/23273798.2016.1212081

Scharinger, C., Soutschek, A., Schubert, T., & Gerjets, P. (2017). Comparison of the working memory load in n-back and working memory span tasks by means of eeg frequency band power and p300 amplitude. *Front Hum Neurosci*, *11*, 6. https://doi.org/10.3389/fnhum.2017.00006

Sharma, D., & McKenna, F. P. (1998). Differential components of the manual and vocal Stroop tasks. *Memory & Cognition*, *26*(5), 1033-1040. https://doi.org/Doi 10.3758/Bf03201181

Shitova, N., Roelofs, A., Schriefers, H., Bastiaansen, M., & Schoffelen, J. M. (2016). Using brain potentials to functionally localise Stroop-like effects in colour and picture naming: Perceptual encoding versus word planning. *Plos One*, *11*(9), e0161052. https://doi.org/10.1371/journal.pone.0161052

Shitova, N., Roelofs, A., Schriefers, H., Bastiaansen, M., & Schoffelen, J. M. (2017). Control adjustments in speaking: Electrophysiology of the Gratton effect in picture naming. *Cortex*, *92*, 289-303. https://doi.org/10.1016/j.cortex.2017.04.017

Shor, R. E., & Orne, E. C. (1962). *Harvard group scale of hypnotic susceptibility*. Consulting Psychologists Press.

Starreveld, P. A., & La Heij, W. (2017). Picture-word interference is a Stroop effect: A theoretical analysis and new empirical findings. *Psychon Bull Rev*, *24*(3), 721-733. https://doi.org/10.3758/s13423-016-1167-6

Strijkers, K., Costa, A., & Thierry, G. (2010). Tracking lexical access in speech production: electrophysiological correlates of word frequency and cognate effects. *Cereb Cortex*, *20*(4), 912-928. https://doi.org/10.1093/cercor/bhp153

Sugg, M. J., & McDonald, J. E. (1994). Time course of inhibition in color-response and word-response versions of the Stroop task. *J Exp Psychol Hum Percept Perform*, *20*(3), 647-675. https://www.ncbi.nlm.nih.gov/pubmed/8027716

Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., & Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Developmental Science*, *12*(1), 106-113. https://doi.org/10.1111/j.1467-7687.2008.00745.x

Tzelgov, J., Henik, A., & Berger, J. (1992). Controlling Stroop effects by manipulating expectations for color words. *Mem Cognit*, *20*(6), 727-735. https://www.ncbi.nlm.nih.gov/pubmed/1435275

van Dinteren, R., Arns, M., Jongsma, M. L., & Kessels, R. P. (2014). P300 development across the lifespan: a systematic review and meta-analysis. *Plos One*, *9*(2), e87347. https://doi.org/10.1371/journal.pone.0087347

van Maanen, L., van Rijn, H., & Borst, J. P. (2009). Stroop and picture-word interference are two sides of the same coin. *Psychon Bull Rev*, *16*(6), 987-999. https://doi.org/10.3758/PBR.16.6.987

West, R., & Alain, C. (1999). Event-related neural activity associated with the Stroop task. *Brain Res Cogn Brain Res*, *8*(2), 157-164. https://www.ncbi.nlm.nih.gov/pubmed/10407204

Yeung, N., Botvinick, M. M., & Cohen, J. D. (2004). The neural basis of error detection: conflict monitoring and the error-related negativity. *Psychological Review*, *111*(4), 931-959. https://doi.org/10.1037/0033-295X.111.4.939

Yuan, P., & Raz, N. (2014). Prefrontal cortex and executive functions in healthy adults: a meta-analysis of structural neuroimaging studies. *Neurosci Biobehav Rev*, *42*, 180-192. https://doi.org/10.1016/j.neubiorev.2014.02.005

Zahedi, A., Abdel Rahman, R., Stürmer, B., & Sommer, W. (2018). *Repository: Common and Specific Loci of Stroop Effects in Vocal and Manual Tasks, Revealed by Event-Related Brain Potentials and Post-Hypnotic Suggestions*

Zahedi, A., Stuermer, B., Hatami, J., Rostami, R., & Sommer, W. (2017). Eliminating stroop effects with post-hypnotic instructions: Brain mechanisms inferred from EEG. *Neuropsychologia*, *96*, 70-77. https://doi.org/10.1016/j.neuropsychologia.2017.01.006

Zinchenko, A., Obermeier, C., Kanske, P., Schröger, E., Villringer, A., & Kotz, S. A. (2017). The Influence of Negative Emotion on Cognitive and Emotional Control Remains Intact in Aging. *Frontiers in Aging Neuroscience*, *9*. https://doi.org/10.3389/fnagi.2017.00349

Appetite

journal homepage: www.elsevier.com/locate/appet

Anoushiravan Zahedi*, Aleksandra Łuczak, Werner Sommer

Humboldt-Universität zu, Germany

ARTICLE INFO

Keywords:
Posthypnotic suggestion
Implicit food preference
Go-No Go task
Classification task
ERP

ABSTRACT

The preference for high-over low-calorie food and difficulties in inhibiting the desire for high-calorie food are important factors involved in unhealthy food choices. Here, we explored posthypnotic suggestions (PHS), aiming to increase the desire for vegetables and fruits, as a possible new tool to induce a preference for low-calorie food. Following the termination of hypnosis, PHS was activated and deactivated in counterbalanced order, while event-related brain-potentials were recorded. Two tasks were administered, a food-face classification measuring implicit food preferences, where stimuli were categorized as showing food items or faces, and a Go-NoGo task measuring inhibition, where food items were selected as being appropriate for making a salad or not. In the food-face classification task without PHS, the early visual P1 component, a marker of stimulus reward-associations, was larger in response to high-than low-calorie food pictures; PHS eliminated this difference. PHS also yielded faster RTs and larger amplitudes of a late positive component in low-versus high-calorie items. Hence, PHS appeared to neutralize the positive perceptual bias toward high-calorie food items and enhance the effective processing of low-calorie items by increasing motivated attention. In the Go-NoGo task, PHS decreased the NoGo-N2; PHS increased the early Go- and NoGo-P3, possibly by turning low- and high-calorie items more pleasant and unpleasant, respectively, requiring more proactive control to inhibit task-irrelevant food-related emotions. Further, in the Go condition, PHS quickened the rejection of salad-inappropriate high-calorie items and increased the amplitude of late-P3, indicating facilitated classification of high-calorie items and increased response monitoring. Together, PHS effectively increased the preference for low-calorie food and the inhibition of impulses toward high-calorie food; therefore, PHS may be a promising tool for supporting healthy and sustainable food choices.

1. Introduction

Unhealthy food preferences and food choices contribute to the global burden of disease and environmental sustainability (Clark, Springmann, Hill, & Tilman, 2019; Forouzanfar et al., 2015; Haddad et al., 2016). For example, the number of obese and overweight individuals with a body mass index (BMI) > 25 has grown steadily in most countries (Rodgers, Woodward, Swinburn, & Dietz, 2018). Traditional measures have fallen short of stopping the obesity epidemic (OECD, 2017) and have yet to show their effectiveness to change diets towards healthier and more environmentally friendly patterns as suggested by the Lancet commission (Willett et al., 2019). Therefore, novel tools are needed to help individuals to shift their food preferences towards healthier choices and resist temptations by unhealthy options. The present study explores posthypnotic suggestions (PHS) as a possible way to modify food preferences. Of the plethora of factors determining food consumption (e.g., Stok et al., 2017), we targeted two psychological variables, food preferences and the inhibition function (Guerrieri, Nederkoorn, & Jansen, 2008; Nederkoorn, Guerrieri, Havermans, Roefs, & Jansen, 2009; Nederkoorn, Houben, Hofmann, Roefs, & Jansen, 2010.)

Preferences for fatty, sweet, or salty food, are central in determining the health outcomes of diets (e.g., Clark et al., 2019) and the global burden of disease (Haddad et al., 2016). For example, obese individuals tend to consume more high-calorie food, rich in sugar and fat in comparison to individuals with normal weight (Ebbeling et al., 2004; Schrauwen & Westerterp, 2000; Seidell, 1998). Food preferences are already influenced in utero and during breastfeeding by the mother's diet (Maier-Noth, 2019; Wilson, 2015) but are subject to alteration or entrenchment throughout life (Emond et al., 2019).

Unhealthy preferences are reinforced by the ubiquitous availability of these kinds of food in modern affluent societies. For some individuals

Corresponding author. Institut für Psychologie, Humboldt-Universität zu, Rudower Chaussee 18, 12489, Berlin, Germany.
E-mail address: zahedian@hu-berlin.de (A. Zahedi).

https://doi.org/10.1016/j.appet.2020.104713
Received 9 January 2020; Received in revised form 9 April 2020; Accepted 9 April 2020
Available online 14 April 2020

overcoming the negative influences of unhealthy food preferences is more difficult than for others. Thus, food consumption is related to the inhibition (Dohle, Diel, & Hofmann, 2018), the executive function (EF) responsible for the suppression of prepotent but inappropriate responses (Diamond, 2013; Miyake et al., 2000). Corroborating this notion, Nederkoorn et al. (2009) observed that implicit preferences for high-calorie food are most detrimental in individuals with low inhibition abilities. In a meta-analysis Yang, Shields, Guo, and Liu (2018) reported significant deficits in inhibition and EFs in over-weight and obese individuals. Blocking EFs with transcranial magnetic stimulation of the left dorsolateral prefrontal cortex (dlPFC) increased consumption of snack food (Lowe, Hall, & Staines, 2014). In adolescents, poor EFs are a predictor of obesity (Tee, Gan, Tan, & Chin, 2018). Finally, individuals with higher BMI showed less efficient EFs (e.g., Prickett, Brennan, & Stolwyk, 2015; Smith, Hay, Campbell, & Trollor, 2011), especially in terms of inhibition (Bartholdy et al., 2017). Therefore, in addition to food preferences, inhibition of reflexive but inappropriate desires appears to be an important factor in food choice.

In the present study, we assessed the effects of PHS, tailored to increase the preference for healthy food and – by implied contrast – inhibit impulses toward high-calorie food. That means, even though we did not expect participants to reject or devalue high-calorie food items as our PHS targeted low-calorie food (fruits, vegetables), it seemed conceivable that participants inhibited their desire for high-calorie items. To understand the mechanisms of PHSs one should consider that hypnosis is a state of consciousness with three central properties, concentration on oneself, dissociation from the surroundings and increased suggestibility (Green, Barabasz, Barrett, & Montgomery, 2005). PHSs are presented during the hypnotic state but will be activated only after the termination of hypnosis by a specific cue such as an associated hand gesture. Multiple studies have shown that, rather than abandoning self-control, hypnosis directs and implements more effectively one's cognitive control repertoire (e.g., Iani, Ricci, Gherri, & Rubichi, 2006; Raz et al., 2003; Raz, Fan, & Posner, 2005; Sheehan, Donovan, & MacLeod, 1988; Zahedi, Stuermer, Abdel Rahman, & Sommer, 2019; Zahedi, Stuermer, Hatami, Rostami, & Sommer, 2017), and may work like a very efficient form of mental practice (Zahedi et al. in prep). In cognitive behavior therapy hypnosis is frequently used to change cognitive biases and preferences towards particular types of stimuli or mental contents (Hertel & Mathews, 2011; Kihlstrom, 2014; Kirsch, Montgomery, & Sapirstein, 1995; Milburn, 2010). Also, it is shown that hypnosis can affect perception; for instance, visual perception (Schmidt, Hecht, Naumann, & Miltner, 2017) and pain perception (Perri, Rossani, & Di Russo, 2019) have been modified successfully with hypnosis; interestingly, in both studies, the changes in perception were related to changes in brain activities, such as the P3 component. Although, to our knowledge, no previous study has applied PHSs to food preferences, in children they can be modified already by simple stories presented outside of any hypnotic context (Duncker, 1938) and also by food advertisements (Emond et al., 2019). It is important to consider that hypnotic-like experiences are defined as conditions where someone is concentrated on a special object and dissociated from other objects, such as in reading an engaging book or watching TV (Shor & Orne, 1962). In this sense, advertisements might be even more similar to hypnosis as they may provoke not only concentration and dissociation but also aim to induce increased suggestibility. Further, in an interesting study, Ludwig et al. (2014) used PHSs to induce disgust toward pictures containing different food categories, when they were superimposed on a background with a specific color, such as green or red. Notably, their PHS was not directed toward the food stimuli themselves but to the background color. The changes in the perception were correlated with decreased activity in the ventromedial prefrontal cortex (vmPFC), possibly showing that PHSs caused participants to devalue objects suggested to be disgusting. Therefore, we expected PHSs to be capable of changing food preferences.

In order to assess the neurocognitive mechanisms underlying the changes obtained by PHSs, we measured event-related brain potentials (ERPs) derived from the EEG elicited by pictures of food. ERPs are a valuable addition to behavioral measures because they provide insight into the cognitive processes mediating between stimuli and responses. Especially as it has been shown that different ERP component, such as P1, N1, P3, and late positivity complex (Allen, Iacono, Laravuso, & Dunn, 1995; Terhune, Cardena, & Lindgren, 2010; Zahedi et al., 2019) were modulated by PHSs in different tasks. Of special interest for the present study was the effect of different categories of depicted food on certain ERP components. The first components of interest were the early visual components P1 and N1, likely generated in extrastriata and inferotemporal cortex, respectively (e.g., Hickey, Chelazzi, & Theeuwes, 2010; Meule, Kubler, & Blechert, 2013; Toepel, Knebel, Hudry, le Coutre, & Murray, 2009). P1 amplitude has been reported to be larger to reward-associated in comparison to neutral or punishment-associated stimuli (Hickey et al., 2010; Schacht, Adler, Chen, Guo, & Sommer, 2012), and was positively correlated with craving for the presented stimuli in smokers (Donohue et al., 2016). Pictures of high-calorie/high-fat food has been reported to elicit a smaller N1 component (150–200 ms) than their counterparts in the studies of Meule et al. (2013) and Toepel et al. (2009).

Another component of interest is the late parietal positivity (LPP) which increases to affective relative to neutral stimuli, and is attributed to motivated attention directed at these items (Schupp, Flaisch, Stockburger, & Junghofer, 2006). LPPs to pictures of food have been reported to be larger than to non-food items, to increase as function of hunger (Nijs, Franken, & Muris, 2008; Nijs, Muris, Euser, & Franken, 2010; Stockburger, Schmalzle, Flaisch, Bublatzky, & Schupp, 2009; Stockburger, Weike, Hamm, & Schupp, 2008), of immediate or delayed consumption (Meule et al., 2013), and whether the depicted food was edible or rotten (Becker, Flaisch, Renner, & Schupp, 2016). Therefore, early and late ERP components appear to be suitable measures of the immediate significance (early components) of food or motivated attention directed at them (LPP).

Some food-related ERP studies tapped into self-regulation or EFs. Thinking about short- or long-term consequences of high- or low-calorie food pictures yielded a positive correlation between emotional eating and the LPP (Meule et al., 2013). Deliberately increasing or decreasing appetite for high-calorie food pictures affected long-latency but not earlier ERP components (Sarlo, Ubel, Leutgeb, & Schienle, 2013). Further, in Go-NoGo tasks, the amplitude of the N2 component to NoGo stimuli – taken as a sign of conflict (Enriquez-Geppert, Konrad, Pantev, & Huster, 2010; Liu, Xiao, & Shi, 2017) - was larger when food rather than non-food items served as NoGo stimuli (Watson & Garvey, 2013) and the N2 amplitude predicted the amount of food consumed after the experiment (Carbine et al., 2017).

For assessing food preferences and EFs, we utilized a face-food classification and a Go-NoGo task, respectively. In the former task, pictures of different food items were presented intermixed with pictures of faces, while participants should classify these two picture categories by choice-response button presses. This calorie-unrelated task of explicitly classifying stimuli into food or face categories (Fig. S.4 in supplementary materials), aimed to distract participants from developing hypotheses regarding the experimenters' intentions and to measure implicit changes in food preference induced by the PHS. As the specific properties of food pictures, such as calorie content or tastiness of the depicted food items, are irrelevant for accomplishing this task, it can be considered to tap into implicit food preferences. As our PHS aimed to render low-calorie items more desirable and attractive, we expected faster responses to the low-calorie items during the PHS-active than in the PHS-inactive condition; no response-related PHS effects were anticipated for high-calorie food items. In the ERPs of the food-face classification task, we expected PHSs-related modulations of P1 and LPP components, indicating alterations in reward-associations and motivated attention, especially to low-calorie items, respectively.

In the Go-NoGo task, participants were instructed to press a button in response to frequent high-calorie food items (Go responses) and withhold their response to infrequent low-calorie items (NoGo condition). NoGo trials are considered to challenge the inhibition function (Jr & Pennington, 1996; Miyake et al., 2000; Roberts; Weisbrod, Kiefer, Marzinzik, & Spitzer, 2000), because during them a frequent and therefore prepotent response shall be withheld. The NoGo-P3 component has been consistently related to inhibition, but the NoGo-N2 was related to different factors, such as response inhibition, conflict monitoring, or emotion regulation (e.g., Albert, Lopez-Martin, & Carretie, 2010; Enriquez-Geppert et al., 2010; Gajewski & Falkenstein, 2013; Liu et al., 2017; Yang et al., 2014; Zhao, Lin, Xie, & Liu, 2019). Notably, emotional stimuli may disrupt the inhibition process (e.g., Rebetez, Rochat, Billieux, Gay, & Van der Linden, 2015; Schulz et al., 2007; Verbruggen & De Houwer, 2007) and affect both N2 and P3 components. Yang et al. (2014) reported, when NoGo stimuli were emotional facial expressions – either positive or negative – rather than neutral expressions, response time to Go stimuli and NoGo-N2 amplitudes decreased. In addition, P3 amplitudes to emotional facial expressions, when serving as Go or NoGo stimuli were bigger than to neutral expressions. Zhao et al. (2019) found that task-irrelevant emotionally positive background pictures reduced the NoGo-N2 amplitude relative to neutral pictures and increased the NoGo-P3, even after strictly controlling for arousal in the emotionally loaded stimuli.

Our PHS aimed to change low-calorie food items into the one and only desirable food category, hence inducing positive emotions toward these items and likely reducing the desirability of high-calorie food items, possibly inducing negative emotions. Therefore, we expected activated PHS to affect both Go and NoGo conditions. Specifically, without PHS we expected pronounced conflicts when the frequent button-pressing response was to be inhibited and, therefore, a salient NoGo-N2 and NoGo-P3 (Enriquez-Geppert et al., 2010; Gajewski & Falkenstein, 2013). However, in the PHS-active condition, as NoGo stimuli should become more desirable and pleasant we expected a smaller NoGo-N2 and an increased NoGo-P3 (Albert et al., 2010; Yang et al., 2014; Zhao et al., 2019). Simultaneously, as in PHS-active condition high-calorie items should become less desirable or even aversive, we expected an increased Go-P3.

2. Methods and materials

2.1. Participants

Although many hypnosis studies include only highly hypnotizable individuals (e.g., Augustinova & Ferrand, 2012; Raz et al., 2003; Raz et al., 2005; Zahedi et al., 2017; Zahedi et al., 2019), testing also medium hypnotizable participants, facilitates generalizing the effects (Jensen et al., 2017). Therefore, in the current study, we included both medium and highly hypnotizable individuals, based on the Harvard group scale of hypnotic susceptibility, form-A (Shor & Orne, 1962, 1963) translated to German (Bongartz, 1985). From 443 (M = 29.0 *years*; *range* = 16–77, SD = 16.4) volunteers in screening sessions, we invited 22 individuals who had obtained more than 7/12 points to the present study, out of whom 12 were medium hypnotizable, that means, they had scores between 7 and 9. In the HGSHS twelve different suggestions are presented to participants, ranging from eyelid catalepsy to heaviness in hands and so forth (Shor & Orne, 1962); based on the objective scores, that is, yes-no questions regarding whether each suggestion was executed or not, a score between 0 and 12 will be assigned to each participant. One participant was unwilling to continue after EEG preparation and another one was excluded due to problems with EEG recordings. Out of 20 final participants (M = 27.3 *years*; *range* = 21–54, SD = 2.12) 14 were female; all were omnivorous and none was obese or anorexic (BMI 20–30). All participants reported normal or corrected to normal visual acuity as well as normal color vision. Based on the participants' report, none of them were diagnosed with a psychological or neurological disorder, and in the last two months none of them had used or withdrawn from any psychoactive drug. The study had been approved by the ethics committee of the Institut für Psychologie of the Humboldt-Universität zu Berlin. Prior to the experiment, signed consent had been obtained. Participation was compensated either with 8 € per hour or course credits.

The sample size of n = 20 in our study was based on two factors: First, on a power analysis with expected effect sizes derived from our previous studies (e.g., Zahedi et al., 2017; Zahedi et al., 2019); the estimated power (Kreidler et al., 2013) for both RTs and ERPs was above recommended values, $1 - \beta > 0.9$ (Cohen, 1988, 2016). Second, on sample sizes of previous PHS studies (e.g., Iani et al., 2006; Iani, Ricci, Baroni, & Rubichi, 2009; Raz et al., 2003; Raz et al., 2005; Sheehan et al., 1988; Zahedi et al., 2017; Zahedi et al., 2019), which were $n_{high-hypnotizable} \leq 20$.

2.2. Hypnosis and post-hypnotic suggestions

The hypnosis narration was recorded in German and presented from tape, in order to provide identical wordings for all participants; however, if participants needed more elaboration, some additional suggestions related to relaxation were presented by the experimenter A.Z., a certified hypnotizer who was present in all sessions. These suggestions were either progressive muscle relaxation (PMR), breathing techniques, or other suggestions similar in nature (Hammond, 1990, 1998). Before hypnosis, participants chose either a forest or beach scenario for the following hypnosis narration. The induction and deepening stages of hypnosis (for detail please see Hammond, 1990; Hammond, 1998), was succeeded by a suggestion about feeling a lightness in the body and by the following PHSs (translated from German):

> "While you are responding to the tasks, you will hear the sound of a bell; and when you have heard it you will feel a lightness in your body (bell). The lightness is like what you have sensed before and retained in your fist, but now another feeling also accompanies this lightness, a craving, voracious desire for vegetables, fruits and all sorts of healthy food. Your stomach contracts with even a picture of vegetables. Even their picture is so desirable and appealing that it increases your appetite, and makes you want to eat them. While you are performing the tasks, whenever you see their picture your appetite and desire for vegetables and fruits, that are very healthy and full of vitamins, will become voracious; and this exclusive desire for vegetables and fruits will get stronger and stronger during the session. When you hear the sound of the bell for the second time, everything will go back to normal, like before the first sound of the bell; even your hunger will disappear like it had never existed; everything will go back to normal."

PHS was given twice in a row in order to consolidate the association with the bell ring. Then, hypnosis was terminated with the countback technique (for detail please see Hammond, 1990; Hammond, 1998).

2.3. Materials and instructions

2.3.1. Food-face classification

Both experimental tasks were programmed in Presentation software (Version 19.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com). In the food-face classification task, 80 food and 80 face pictures were presented twice, in random order on a white background (i.e., 320 trials in total), requiring choice responses with the index fingers between food and face pictures; the assignment of index fingers to picture categories was counterbalanced. Thus, participants were asked to decide whether a presented picture contained a face or a food item. This task ensured that participants attended to all stimuli, without demanding any differentiation between food categories, such as high- versus low-calories. Notably, as task demands were the same for all food items, any observed differences in ERP or performance between different food categories can be attributed to the perception and processing of food categories rather than tasks or strategies.

Face pictures showed either neutral or happy facial expressions. The food items had two levels of calorie content, that is, high- and low-calorie, and two levels of valence, that is, neutral and positive valence, resulting in 40 trials in each subcategory (e.g., low-calorie, high valence). Food pictures were adopted from the database of Blechert, Meule, Busch, and Ohla (2014) and controlled for color composition, contrast, brightness, size, and image complexity (please see supplementary materials for details). At the beginning of the task, participants were familiarized with the task by five practice trials during which feedback was given; during the subsequent trials, no feedback was provided. Each trial started with a fixation cross presented for 500 ms, replaced by a picture for 1000 ms, and followed a 500-ms blank screen. Trials were terminated as soon as a response was produced or after 2s. Reaction times (RT) were defined as the interval between stimulus and button press onset; correct responses were defined as pressing the button associated with the picture category; all other responses (i.e., no response or pressing the wrong button) was considered errors.

2.3.2. *Go-NoGo task*

The Go-NoGo task consisted of 80 high- and 40 low-calorie food pictures, representing the Go- and NoGo-trials, respectively. The following task instruction was given:

> "Imagine that you are to make a salad. Please press the button in response to any item that you do not want to put into the salad, and refrain from responding when you want to put an item into the salad."

Hence, for successful task completion, participants should respond to the 80 high-calorie food pictures (i.e., Go trials) and refrain from pressing the button for the 40 low-calorie food pictures (i.e., NoGo trials). Pictures for the Go-NoGo task were adopted from the database of Blechert et al. (2014). Pictures of both categories were comparable with respect to color composition, contrast, brightness, size, complexity, and valence (please see supplementary materials for details). The response finger for the Go trials was fixed for each participant but counterbalanced across the sample. Five practice trials were used at the beginning of the task where participants received feedback; no feedback was provided thereafter. The pictures were shown on a white background in randomized order with each trial lasting 2 s; each trial started with a fixation cross, shown for 500 ms, replaced by a picture for 1000 ms, followed by a 500-ms blank screen. Trials terminated either after 2 s or with the response. RTs were defined as the interval from stimulus onset to button press. Button presses to high-calorie items and their absence to low-calorie items was considered correct responses; everything else was considered as an error (i.e., no response after high-calorie or response after low-calorie).

2.4. *Design and procedure*

Participants were to abstain from eating at least 2 h prior to coming to the study, which resulted in an abstention period of at least 4 h before the tasks started. After participants had completed a demographic questionnaire, the EEG cap was mounted, followed by hypnosis induction, including PHS. After termination of hypnosis, both experimental tasks were administrated twice, with PHS activated or deactivated. The order of tasks was fixed, with the food-face classification task administered first and the Go-NoGo task second. For each participant, one run of the tasks was with PHS activated and the one with PHS deactivated; the order of PHS activation conditions was counterbalanced. After the tasks, sample of horizontal and vertical eye-movements and blinks were recorded, to be used for offline eye-movement corrections.

During tasks participants sat on a chair approximately 70 cm away from the monitor, resulting in a viewing angle of ± 1.5° for the stimuli used. The whole session lasted about 3.5 h, including 1 h of EEG preparation, 1 h of hypnosis, and finally 45 min for each run of experimental tasks.

2.5. *EEG recordings and pre-analyses*

EEG was recorded from 44 Ag/AgCl electrodes, mounted in an elastic cap (Easy Cap, FMS GmbH, München, Germany), according to the 10–20 international system, and 6 electrodes located outside of the cap. Four of these external electrodes were used for EOG recordings, two electrodes below each eye for vertical EOG, and two at the outer canthi for the horizontal EOG; two electrodes were placed at the mastoids, with the left one serving as online reference. Signals were recorded with Brainamps DC amplifiers (Brain Products GmbH, München, Germany), at a sampling rate of 500 Hz without additional filters. Impedances were kept below 10 kΩ. Triggers for stimuli and responses were inserted online into the EEG data by synchronization between Presentation software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) and BrainVision Recorder (Brain Products GmbH, München, Germany).

After recordings, EEG data were recalculated to average reference. For eye movement artifact correction, the recorded samples for horizontal and vertical eye movements and blinks were fed into the BESA Research 6.0 software and rectifier matrices were produced for each participant and applied to their EEG recordings by a linear derivation method. Electrophysiological data were bandpass filtered at 0.05–40 Hz and the raw data inspection functions, consisting of standard criteria such as Min-Max (200 μV in 200 ms), low-activity (0.05 in 200 ms) and max gradient (200 μV in 200 ms), were applied to reject segments with artifacts. Data were segmented, averaged, and analyzed with EEGLAB (Delorme & Makeig, 2004). Further, all segments with other artifacts, and/or incorrect or missing responses were eliminated, resulting in a loss of less than 10% of all trials. In order to reduce the smearing effects of trial to trial latency variability, especially in late components, we reconstructed the ERP signals after latency correction with residue iteration decomposition (RIDE) (Ouyang, Sommer, & Zhou, 2015).

2.6. *Data analyses*

All behavioral data analyses were conducted using R software (http://www.R-project.org/.); for ERP data analyses MATLAB (version 8.6.0 (R2015b). Natick, Massachusetts: The MathWorks Inc.) was employed. For statistical testing, analysis of variance (ANOVA) was utilized with repeated measurement factors PHS activation (active vs. inactive), Calorie (high vs. low), and – when applicable - Valence (high vs. neutral) and – for behavioral data – order as between-subject variable (active-inactive (AI) vs. inactive-active (IA)). For post-hoc tests, the Bonferroni correction was used, and adjusted p-values are reported; for planned post-hoc tests of a priori hypotheses, we did not apply Bonferroni corrections.

3. Results

3.1. *Food-face classification*

3.1.1. *Performance*

Food and face stimuli were analyzed separately because the experimental factors differed. ANOVA of RTs to food stimuli (Fig. 1A and B) revealed a main effect of calorie content, $F(1,\ 18) = 4.9,\ p < .05,\ \eta_p^2 = .21$, an interaction of calorie content and PHS, $F(1,\ 18) = 5.1,\ p < .05,\ \eta_p^2 = .22$, and a three-way interaction between calorie content, PHS and order of PHS activation, $F(1,\ 18) = 6.1,\ p < .05,\ \eta_p^2 = .25$. Planned post-hoc *t*-tests of the two-way interaction between calorie content and PHS, showed no calorie effect when PHS was inactive $(\overline{\text{High.cal} - \text{Low.cal}} =$

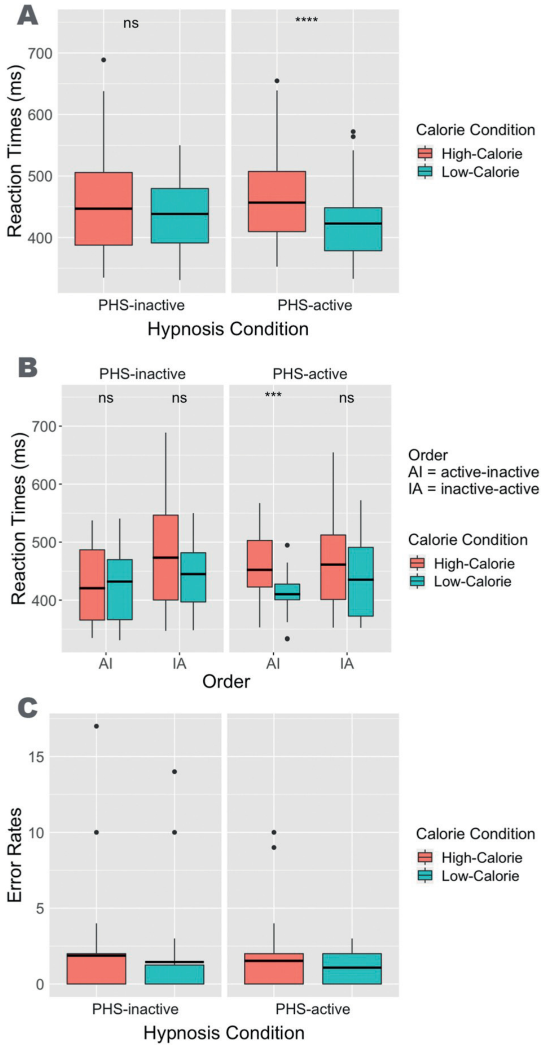


Fig. 1. Performance in the food-face classification task. Means and interquartile distances, and outliers are given as a function of PHS activation condition and calorie content, and post-hoc tests between calorie content are shown, for (A) RTs and (C) error rates. (B) Means and interquartile distances as function of PHS activation condition, calorie content and PHS activation order and contrasts between calorie content for RTs.

8.4 ms, $SD = 57.4$ ms) but faster responses to low calorie items when PHS was active ($\overline{\text{High.cal} - \text{Low.cal}} = 33.0$ ms, $SD = 45.2$ ms), $p < .001$. For the three-way interaction between calorie content, PHS and order of PHS condition, post-hoc *t*-tests showed that in the inactive-active order, the calorie effect was significant in the PHS-active condition ($\overline{\text{High.cal} - \text{Low.cal}} = 39.2$ ms, $SD = 51.4$ ms), $p < .001$.

For error rates (Fig. 1C), ANOVA showed a three-way interaction between calorie content, PHS and order of PHS conditions, $F(1, 18) = 5.4$, $p < .05$, $\eta_p^2 = .23$. However, post-hoc tests did not yield any specific calorie effects.

For face stimuli, ANOVA did not reveal any main effects or interactions between factors in RTs or error rates.

3.1.2. Event-related potentials

ERPs to face and food stimuli were analyzed separately because experimental factors and important aspects of ERP waveforms differed. In food picture-elicited ERPs the P1 component (Fig. 2A) was measured in the 90–140 ms time window at a posterior ROI (electrodes P8, PO9, PO7, PO8, PO10, O2 and Iz). ANOVA showed a main effect of calorie content, $F(1, 19) = 5.4$, $p < .05$, $\eta_p^2 = .22$, and an interaction between calorie content and PHS, $F(1, 19) = 5.2$, $p < .05$, $\eta_p^2 = .21$; no other main effects or interactions were present. Planned post-hoc tests revealed a significant calorie effect in the PHS-inactive condition ($\overline{\text{High.cal} - \text{Low.cal}} = 0.48\ \mu\text{V}$, $SD = .15$), $F(1, 19) = 9.6$, $p < .01$, $\eta_p^2 = .34$, but none in the PHS-active condition ($\overline{\text{High.cal} - \text{Low.cal}} = 0.05\ \mu\text{V}$, $SD = .14$), $F < 1$. Further, although the low-calorie P1 amplitude increased in the PHS-active relative to the -inactive condition ($\overline{\text{PHS.active} - \text{PHS.inactive}} = 0.35\ \mu\text{V}$, $SD = .12$), $F(1, 19) = 8.5$, $p < .01$, $\eta_p^2 = .30$, the high-calorie amplitude did not differ between the PHS conditions ($\overline{\text{PHS active} - \text{PHS.inactive}} = -.08\ \mu\text{V}$, $SD = .13$), $F < 1$. For the face-elicited P1 (Fig. 2B), measured in the same ROI and time window, there were no experimental effects.

For the N1 component (Fig. 2A), measured in a posterior ROI (electrodes P7, P8, PO9, PO7, PO8, PO10, O1, Oz, O2 and Iz) during the 130–180 ms time window, ANOVA revealed only a calorie content effect ($\overline{\text{High.cal} - \text{Low.cal}} = 0.15\ \mu\text{V}$, $SD = .08$), $F(1, 19) = 4.9$, $p < .05$, $\eta_p^2 = .20$. For the N170 to faces (Fig. 2bB), measured in the same ROI and time window, there was a valence effect ($\overline{\text{Pos.val} - \text{Neu.val}} = 0.27\ \mu\text{V}$, $SD = .12$), $F(1, 19) = 5.9$, $p < .05$, $\eta_p^2 = .23$

Right. Topographies of average ERPs across all conditions (map scaling: -3.0 to $3.0\ \mu\text{V}$), effects of calories (high minus low), hypnosis (PHS active minus PHS inactive) and valence (positive minus negative); map scaling: -0.5 to $0.5\ \mu\text{V}$. Green electrode sites show the ROIs used for the analyses.

For LPP (Fig. 3aA), measured in the 280–580 ms time window at a central ROI (electrodes Cz, CP1 and CP2), ANOVA revealed an interaction between calorie content and PHS, $F(1, 19) = 5.0$, $p < .05$, $\eta_p^2 = .21$. Planned post-hoc tests revealed that LPP amplitudes were not significantly different in the PHS-inactive condition ($\overline{\text{Low.cal} - \text{High.cal}} = 0.0\ \mu\text{V}$, $SD = .17$), $F < 1$; however, in the PHS-active condition the P3 amplitude to pictures of low-calorie food was significantly bigger than to high-calorie items ($\overline{\text{Low.cal} - \text{High.cal}} = 0.44\ \mu\text{V}$, $SD = .20$), $F(1, 19) = 5.2$, $p < .05$, $\eta_p^2 = .21$. In the same ROI, within the 580–730 ms time window, ANOVA showed a trend for larger amplitudes during the PHS active than in the inactive condition, $F(1, 19) = 3.7$, $p = .06$, $\eta_p^2 = .15$.

For face-elicited ERPs (Fig. 3B), there were no experimental effects, neither in the 280–580 ms or 580–730 ms time windows.

Right. Topographies of average ERPs for effects of calories (low minus high) and hypnosis (PHS active minus inactive); map scaling: -0.5 to $0.5\ \mu\text{V}$. Green electrode sites show the ROIs used for the analyses.

3.2. Go-NoGo task

3.2.1. Performance

For the Go-NoGo task, all Go and NoGo trials showed high- and low-calorie food pictures, respectively; valence was controlled across stimulus categories and, hence, was no experimental factor. ANOVA of RTs (Fig. 4) revealed a main effect of PHS, $F(1, 18) = 9.4$, $p < .01$, $\eta_p^2 = .34$, because participants were faster in responding to high-calorie pictures during the PHS-active than -inactive condition ($\overline{\text{PHS.active} - \text{PHS.inactive}} = -21.1$ ms, $SD = 30.9$). ANOVA of error rates did not yield any significant effects for either the Go ($\overline{\text{PHS.active} - \text{PHS.inactive}} = 0.6$, $SD = 4.2$) or NoGo condition ($\overline{\text{PHS.active} - \text{PHS.inactive}} = 0.4$, $SD = 2.0$).

3.2.2. Event-related potentials

In the Go-NoGo task we focused on the P2–N2 and P3 components. For the P2–N2 both frontal and parietal regions were selected (for

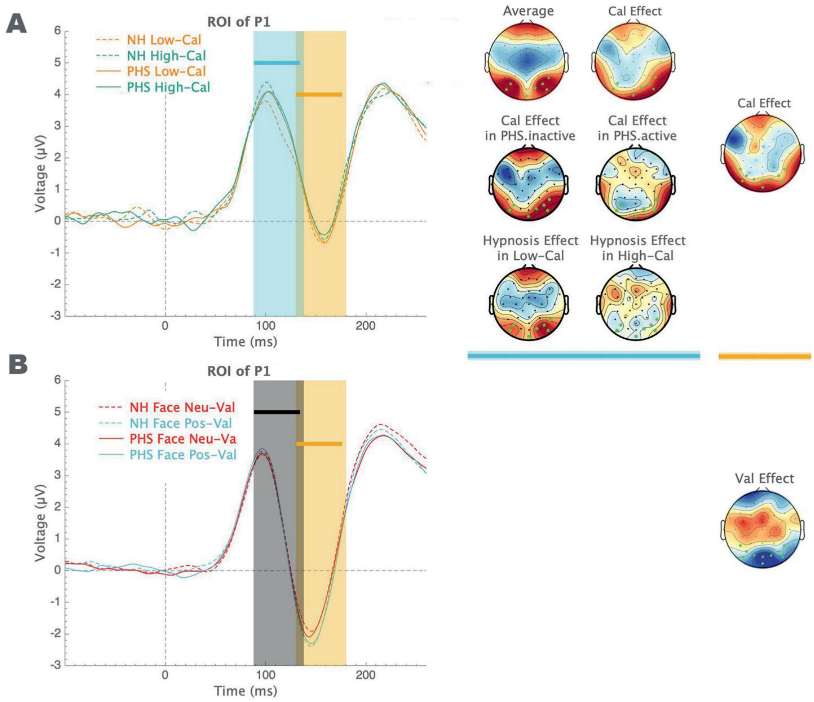


Fig. 2. Left. Grand average ERPs for the P1 ROI to (A) food pictures of different calorie contents and PHS activation conditions and (B) to faces of neutral and positive valence and PHS activation conditions. Highlighted areas show the time windows used for analyses.

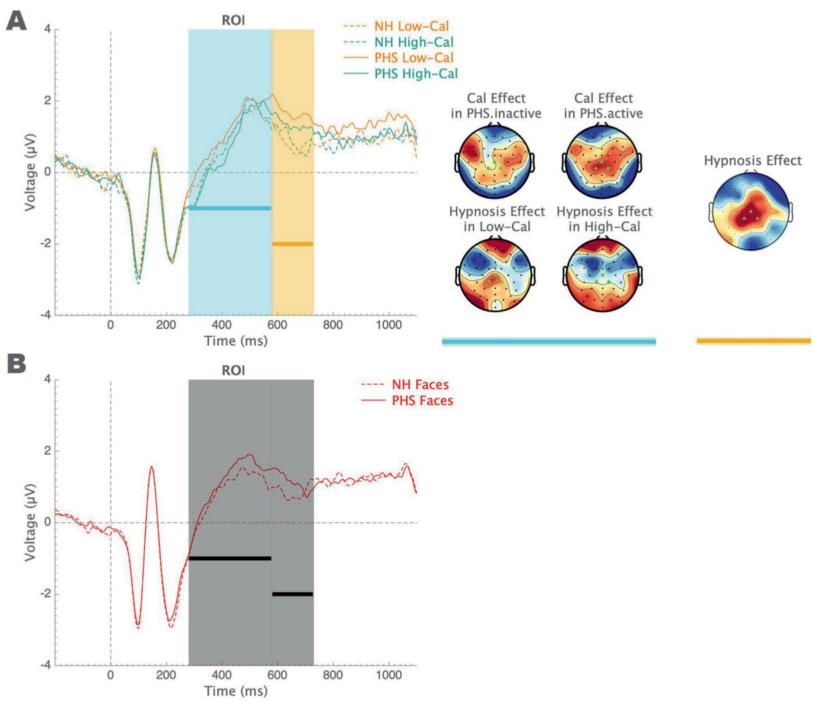


Fig. 3. Left. Grand average ERPs for the P3 ROI to (A) food pictures of different calorie content and PHS activation conditions and (B) to faces of different PHS activation conditions. Highlighted areas show the time windows used for analyses.

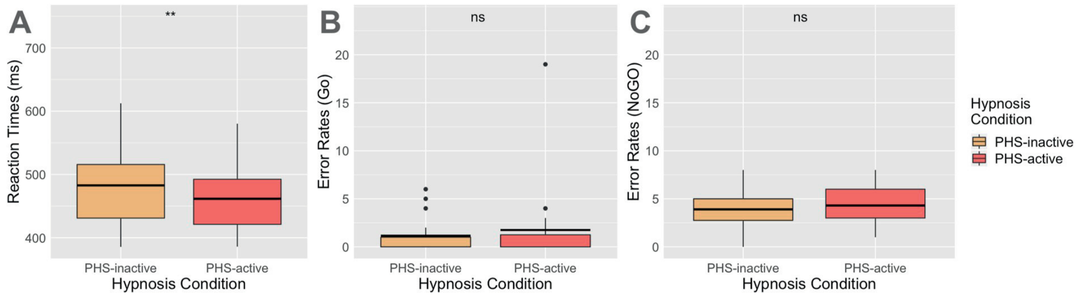


Fig. 4. Performance in the Go-NoGo task. Means and interquartile distances as a function of PHS condition, and ANOVA results are shown for (A) RTs, (B) error rates in the Go condition (commission errors), and (C) in the NoGo condition (omission errors).

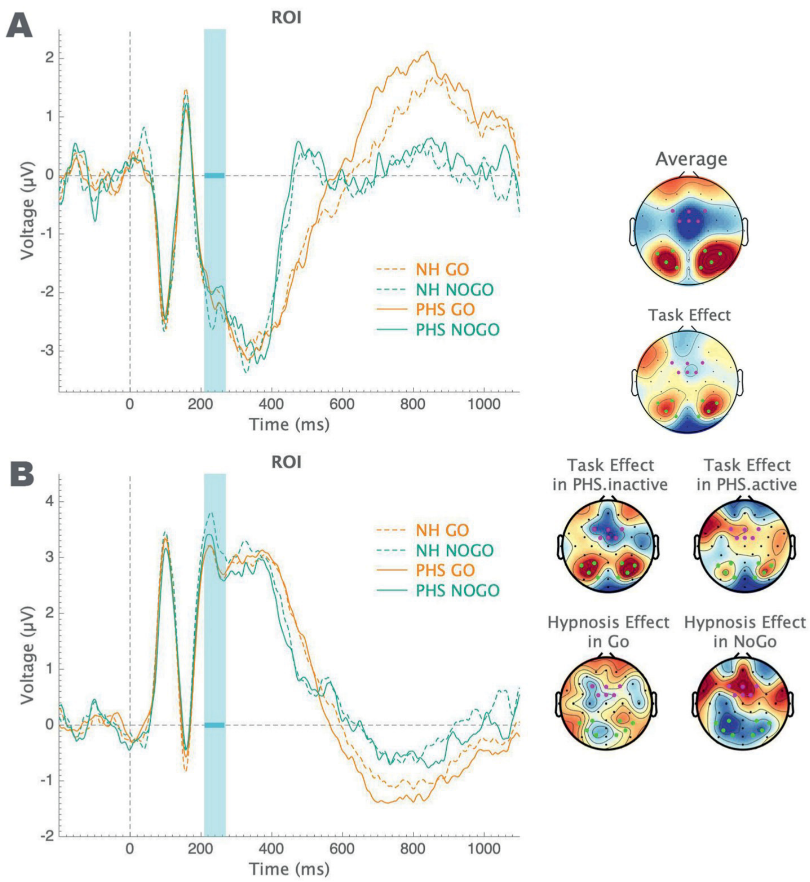


Fig. 5. Left. Grand average ERPs superimposed for Go and NoGo and PHS activation conditions for (A) frontal and (B) parietal ROIs. Highlighted areas show the time windows used for the analyses.

review please see Folstein & Van Petten, 2008; Polich, 2007). In a frontal ROI (electrodes F3, Fz, F4, FC1, FCz and FC2), during the 210–270 ms time window (Fig. 5A), ANOVA with repeated measures factors Go-NoGo condition and PHS activation showed an interaction between both factors, $F(1, 19) = 5.6$, $p < .05$, $\eta_p^2 = .22$. Planned post-hoc comparisons in the PHS-inactive condition revealed a strong Go-NoGo effect ($\overline{\text{NoGo} - \text{Go}} = -0.34\,\mu\text{V}$, $SD = .18$), $F(1, 19) = 5.5$, $p < .05$, $\eta_p^2 = .22$, which was absent in the PHS-active condition ($\overline{\text{NoGo} - \text{Go}} = .13\,\mu\text{V}$, $SD = .18$), ($F < 1$). In addition, there was a significant PHS effect in the NoGo condition ($\overline{\text{PHS.active}-\text{inactive}} = 0.42\,\mu\text{V}$, $SD = .16$), $F(1, 19) = 6.9$, $p < .05$, $\eta_p^2 = .26$, but not in the Go condition ($\overline{\text{PHS.active}-\text{inactive}} = -0.09\,\mu\text{V}$, $SD = .12$), ($F < 1$).

In the same time window a parietal P2 ROI (electrodes P7, P3, P4, P8, PO7, PO8, O1 and O2) (Fig. 5B), showed a main effect of Go-NoGo condition, $F(1, 19) = 5.7$, $p < .05$, $\eta_p^2 = .23$, and an interaction between the Go-NoGo condition and PHS activation, $F(1, 19) = 5.9$, $p < .05$, $\eta_p^2 = .23$. Again, planned post-hoc tests in the PHS-inactive condition, revealed a strong Go-NoGo effect ($\overline{\text{NoGo} - \text{Go}} = .47\,\mu\text{V}$, $SD = .12$), $F(1, 19) = 14.1$, $p < .001$, $\eta_p^2 = .42$,

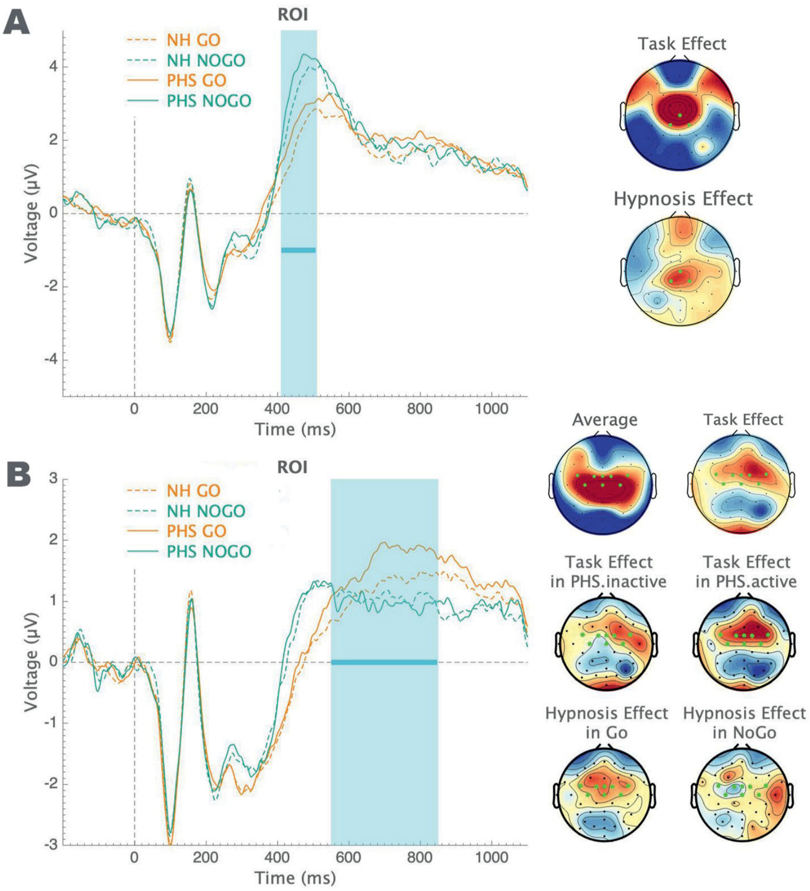


Fig. 6. Left. Grand average ERPs superimposed for different task and PHS activation conditions for (a) the early P3 and (b) the late P3. Highlighted areas show the time windows used for the analyses.

which was absent in the PHS-active condition ($\overline{\text{NoGo} - \text{Go}} = .05\ \mu\text{V},\ SD = .15$), ($F < 1$). Furthermore, a significant PHS effect was present only in the NoGo condition ($\overline{\text{PHS.active}-\text{inactive}} = -0.38\ \mu\text{V},\ SD = .18$), $F(1,\ 19) = 4.4$, $p < .05$, $\eta_p^2 = .19$, but not in the Go condition ($\overline{\text{PHS.active}-\text{inactive}} = .02\ \mu\text{V},\ SD = .11$), ($F < 1$). Together, the results for both the anterior and posterior N2 ROIs indicate a clear N2 to NoGo-stimuli without PHS, which was abolished by PHS activation.

Right. Topographies of average ERPs across all conditions (map scaling: -2.0 to 2.0 µV), effects of Go-NoGo conditions (NoGo minus Go) and hypnosis (PHS-active minus PHS-inactive); map scaling: -0.5 to 0.5 µV. Green and magenta electrodes show the P2- and N2-ROIs, respectively.

In ERP waveshapes and topographies two subcomponents of P3 were distinguishable, an early P3 (Fig. 6A) in the NoGo and a later P3 (Fig. 6B) in the Go condition (for review please see Polich, 2007). The early P3 was measured in the 410–510 ms time window in a centroparietal ROI (electrodes Cz, CP1 and CP2). ANOVA showed a main effect of PHS ($\overline{\text{PHS.active}-\text{inactive}} = 0.48\ \mu\text{V},\ SD = .22$), $F(1,\ 19) = 4.6$, $p < .05$, $\eta_p^2 = .19$, and a main effect of Go-NoGo condition ($\overline{\text{NoGo} - \text{Go}} = 1.23\ \mu\text{V},\ SD = .34$), $F(1,\ 19) = 13.0$, $p < .005$, $\eta_p^2 = .40$.

For the late P3 (Fig. 6B), measured in the 550–850 ms time-window at a frontocentral ROI (electrodes FC5, FC1, FCz, FC2, FC6, C3, Cz and C4), ANOVA indicated a main effect of Go-NoGo condition, $F(1,\ 19) = 5.3$, $p < .05$, $\eta_p^2 = .21$, and an interaction between PHS activation and Go-NoGo condition, $F(1,\ 19) = 8.1$, $p < .05$, $\eta_p^2 = .29$. Planned post-hoc tests revealed a significant PHS effect in the Go condition ($\overline{\text{PHS.active}-\text{inactive}} = 0.33\ \mu\text{V},\ SD = 20$), $F(1,\ 19) = 4.4$, $p < .05$, $\eta_p^2 = .19$, but not in the NoGo condition ($\overline{\text{PHS.active}-\text{inactive}} = -0.10\ \mu\text{V},\ SD = .17$), ($F < 1$); further, there was no Go-NoGo effect when PHS was inactive ($\overline{\text{Go} - \text{NoGo}} = 0.13\ \mu\text{V},\ SD = .18$), $F < 1$, but it was very clear when PHS was active ($\overline{\text{Go} - \text{NoGo}} = 0.68\ \mu\text{V},\ SD = .21$), $F(1,\ 19) = 9.9$, $p < .01$, $\eta_p^2 = .34$.

Right. Topographies of average ERPs across all conditions, effects of task (for the early P3: NoGo minus Go, and for the late P3: Go minus NoGo) and hypnosis (PHS-active minus PHS-inactive).

For the early P3 topographies map scaling: -0.8 to 0.8 µV.

For the late P3 topographies map scaling: -1 to 1 µV. Green electrodes show the ROI used for the analyses.

4. Discussion

By employing two tasks and ERP recordings, we explored the effects of PHS to increase the value of low-calorie food over high-calorie food by inducing craving and desire for salads, fruit and vegetables in response to pictures of these food items. A food-face classification task did not involve calorie content as task-relevant dimension but required the classification of pictures as representing food or faces. A Go-NoGo task explicitly required the categorization of food items as being suitable or non-suitable for making a salad, aligning with the distinction of low- and high-calorie items. Therefore, calorie content of the depicted food was an explicit part of the task. Since the task was devised as Go-NoGo, it measured the inhibition function and its modulation by PHS.

4.1. Food-face classification results

In the food-face classification task, responses during PHS activated – but not during PHS inactivated - were faster to low-as compared to high-calorie food items, demonstrating the transfer of PHS to crave for low-calorie food into performance. As calorie content was irrelevant to the task at hand, faster responses to low-calorie items indicate that these stimuli were implicitly processed more efficiently. This finding is in line with the idea that a positive bias toward a specific type of stimuli, especially when they are relevant for the current concern of the individual (e.g., hunger or desire), increases the effectiveness of stimulus processing (for review please see Pool, Brosch, Delplanque, & Sander, 2016).

ERPs shed light on the mechanisms behind this performance effect of PHS. It is remarkable that already around 100 ms (90–140 ms) high-calorie pictures elicited a bigger P1 amplitude in response to high-calorie images when PHS was inactive. Importantly, activation of PHS eliminated the differences in P1 amplitude in response to low-versus high-calorie pictures. As the P1 amplitude has been reported to be bigger in response to reward-associated stimuli (Hickey et al., 2010), and to be positively correlated with craving (Donohue et al., 2016), the present results seem to indicate that without PHS our participants craved for high-calorie food; this is plausible because at the time of testing they had abstained from food for at least 4 h and probably were at least slightly hungry. However, when PHS was activated, it neutralized the initial bias for high-calorie food. This alteration in early neural responses during visual processing indicates that PHS effects are not confined to deliberately increasing or decreasing appetite (Sarlo et al., 2013) but may affect more elementary processing stages. To our knowledge, this is the earliest effect of calories reported so far. Other studies have also reported rather early – albeit somewhat later – calorie effects in the N1 component (Meule et al., 2013; Toepel et al., 2009). However, different food abstention-durations might have contributed to different observations in P1, as hunger can affect the rewarding value of food stimuli. In Meule et al. (2013) study participants had abstained from food for 2 h, hence for a shorter amount of time than in the present study; Toepel et al. (2009) had not reported abstention duration. We should point out that the presence and absence of P1 amplitude as a function of PHS inactive and active, respectively, rules out that the P1 effect is due to low-level visual differences of stimuli because PHS activation conditions were balanced in order and stimuli had been controlled for a number of important low-level properties. These results complement imaging studies showing that high- and low-calorie food cues are processed differently in the brain (Frank et al., 2010; Killgore et al., 2003) and that this distinction is made automatically and rather early during visual processing.

A reverse effect as in the P1 was found in the LPP amplitude (280–580 ms). Here, no calorie effect was present when PHS was inactive, apparently in line with similar negative findings of others (e.g., Becker et al., 2016; Meule et al., 2013). Interestingly, activating PHS markedly changed this situation, increasing the amplitude of the LPP to low-relative to high-calorie items. Effects of affect or emotion in this late positive potential are usually interpreted as a sign of increased motivated attention (Sarlo et al., 2013). Summarizing, inducing an early positive bias for low-calorie food by PHS, suggesting to desire low-calorie stimuli caused more efficient processing of low-calorie food items, which was shown in faster response times (Hickey et al., 2010; Pool et al., 2016), and directed motivated attention towards these items, as indicated by increased LPP amplitudes (Donohue et al., 2016; Sarlo et al., 2013).

Finally, it is worthwhile to mention that the responses and ERPs to faces did not show any effects of PHS, demonstrating that the observed effects with respect to food stimuli were domain specific.

With regard to ERP components reflecting the association of stimuli with reward, we targeted the P1 component in the food-face classification task. Previous studies have shown the P1 to be larger to stimuli that were associated with higher degrees of reward (e.g., Donohue et al., 2016; Hickey et al., 2010; Schacht et al., 2012); therefore, the P1 amplitude seems to be a marker of the perceived associational value of stimuli with reward. Since we were interested in the perceptual changes induced by PHS in associational reward values of a stimulus, the P1 amplitude appeared to be a suitable target component. Of note, components associated with response outcome, such as the feedback-related negativity (FRN) (e.g., Fromer, Sturmer, & Sommer, 2016) or reward positivity could not be employed since in our food-face discrimination task no feedback regarding performance was given. Further, the FRN, usually analyzed in the 200–400 ms time window in feedback stimulus-synchronized ERPs, is closely related to response adjustments and learning after response production. However, since in our task no feedback was present no adjustments of response were expected, and therefore, the FRN was not applicable.

4.2. Go-NoGo task results

In the Go-NoGo task, the calories of the depicted food were explicitly relevant for the task, which required pressing a button to high-calorie food items, unsuitable for making a salad, and to withhold this response to salad-suitable low-calorie food items. Hence, we expected that (1) without PHS, inhibition would be required to suppress the prepotent response of pressing a button when an infrequent, non-preferred, low-calorie item rather than a preferred, frequent, high-calorie item was presented. (2) When PHS was activated, the low-calorie food items should be the only desired food category (i.e., elicit positive emotions), and high-calorie food items should be diminished in desirability or even elicit negative emotions.

These hypotheses were supported by neural data. The differences between high and low-calorie items in the anterior N2 component, which is considered to indicate response inhibition, emotional regulation or conflict-monitoring (Albert et al., 2010; Enriquez-Geppert et al., 2010; Folstein & Van Petten, 2008; Ouyang, Schacht, Zhou, & Sommer, 2013), and its posterior P2 counterpart, were clearly present when PHS was deactivated but vanished when PHS was activated. Furthermore, PHS increased both Go-P3 and NoGo-P3. These findings are in line with reports of Yang et al. (2014) and Zhao et al. (2019) that the NoGo-N2 was decreased when the eliciting stimulus was emotionally arousing rather than neutral, whereas Go-P3 and NoGo-P3 were increased. The reasons why emotions disrupt inhibition in Go-NoGo tasks (e.g., Rebetez et al., 2015; Schulz et al., 2007; Verbruggen & De Houwer, 2007) might be that stimulus-induced emotional arousal is an automatic response which is not relevant and even disruptive for the task at hand and needs to be inhibited. This may be akin to the situation in Stroop tasks where word meaning is irrelevant and disruptive. In the Stroop task, when participants had to deploy more inhibition, an amplitude decrease in N2 and increase in P3 have been observed (Zahedi et al., 2019). Therefore, emotionally arousing Go and NoGo stimuli may require more proactive control (Braver, 2012) in order to inhibit disruptive emotional response, inflating Go- and NoGo-P3, and decreasing NoGo-N2.

In both PHS-inactive and -active conditions, the early P3 was bigger in the NoGo than in the Go and the late P3 was bigger in NoGo condition in comparison to Go, which is common finding (e.g., Gajewski & Falkenstein, 2013; Liu et al., 2017; Polich, 2007; Yang et al., 2014; Zhao et al., 2019). As only in No-Go situations it is necessary to inhibit a prepotent response, the early P3 component, which might be related to recruitment of cognitive control (Polich, 2007; Zahedi et al., 2019) expectedly was bigger in the NoGo than in the Go condition. However, the late P3, mostly following the response, might be related to response monitoring (Polich, 2007), and therefore, might have been more pronounced in Go than in No-Go trials.

In the Go-NoGo task, we also found that during activated PHS, Go-responses were quickened. It is important to consider that in the present design, the response terminated stimulus presentation, and therefore, in our task faster responses might be considered as an escape from an emotionally negative situation. Yang et al. (2014) had also observed faster responses to emotional facial expressions as compared to neutral faces. It seems that more proactive control deployed due to emotional contents of stimuli, enhances their detection and processing, manifested in shorter RTs to Go stimuli.

4.3. Limitations and perspectives

Here it is necessary to discuss some points regarding different aspects of our study. First, in our Go-NoGo task, the instructions requested participants to imagine making a salad and to decide, which items they did not want to put into the salad, with the assumption that participants would exclude (by button press) high-calorie items and include (by not responding) low-calorie items. One might argue, that some participants might have wanted to include meat or cheese, that is, high-calorie items, in their salad. However, our high-calorie pictures did not show such items that could be deemed appropriate for a salad (e.g. diced or sliced cheese or meat); in addition, error rates were very low in the Go-NoGo task, indicating that the paradigm worked as intended.

Noticeably, as we used a Go-NoGo task in which the assignment of the low- and high-calorie items to Go and NoGo conditions were fixed and did not include pictures of non-food items, we cannot rule out that the observed effects are not specific for the nutrition value or even for food items. However, in the food-face classification task, PHS effects had proven to be food-specific. Future studies aiming at the inhibition function might investigate the specificity of the effects by using also a reverse assignment of low- and high-calorie items to Go and NoGo conditions and a condition with non-food items.

Second, in the present study, since we included medium-hypnotizable participants as well as high-hypnotizable participants, according to the normative data (Bongartz, 1985; Shor & Orne, 1962, 1963), our sample is representative of about 61–75% of the normal population. Although our results cannot be generalized to the whole population, the current study is among the first to attempt to enhance the generalizability of PHS effects by including also medium-hypnotizable participants as suggested by Jensen et al. (2017).

Third, one may ask whether the present design precluded confounds with task demands. For the design of PHS studies it is important to point out that hypnosis induces relaxation (e.g., Kirsch et al., 1995; Klein & Spiegel, 1989; London, 1961; London, Cooper, & Johnson, 1962; Lynn et al., 2019; Milburn, 2010), which might induce a confound, when PHS after hypnosis is compared with a condition without hypnosis (Zahedi et al., 2017). In order to control for such a confound, we administrated hypnosis with PHS at the beginning of our single session, followed by activating and deactivating PHS in counterbalanced order. Therefore, our design effectively reduces many potential confounds, such as relaxation due to hypnosis, demand characteristics, or order of testing. Further, even though our PHS explicitly suggested an increase in desire for low-calorie food, our PHS did not include any demands, instructions or strategies with regard to the task performance (i.e., classifying faces and food, or selecting food items, suitable for making a salad). In particular, one of our tasks assessed implicit preferences by asking participants to respond to food items, that is, to both high- and low-calorie items, with the same finger. Hence, the task demanded the exact same response in order to prevent participants to develop any hypotheses regarding the experimenters' intentions. Also, the ERP components used are very hard to be altered intentionally, especially early components such as the P1 component, and our stimuli were matched for low-level properties (for details please see the supplementary materials. Together, the multiple controls included in the design intended to obscure as much as possible the hypotheses of the study and ensure that changes in the participants' reactions were due to PHS.

Furthermore, our design utilized a counterbalanced repeated-measures design with a fixed order of tasks within each PHS condition, in which we randomly but in equal proportion assigned participants to PHS activated - PHS inactivated or PHS inactivated – PHS activated condition orders. Therefore, factors such as practice, fatigue and hunger were controlled. And even though the Go-NoGo task was always the second of two tasks, we should point out that we did not compare the effects of the Go-NoGo with the food-face classification task, but only compared the effects of a given task between PHS activated or PHS deactivated. Therefore, as the Go-NoGo was always the second task, the observed results could not be attributed to other factors such as practice, hunger or fatigue; the same reasoning holds true for the food-face decision task. Furthermore, the tasks that we employed were designed to be concise with durations of less than 20 min and participants received enough resting-time in between tasks in order to ensure that time on task would not affect results. Furthermore, the food-face classification task was short and easy it is unlikely that the Go-NoGo task effects would depend on the position of the task within the block.

One of the interesting questions, which can be investigated next is how individual differences in food preferences might relate to PHS effects in larger samples. Notably, the main goal of the current study was to investigate whether PHSs can affect food preferences. Other questions of interest would be the endurance of the effects over time and their transfer to real life situations.

5. Conclusions

In conclusion, the results of the food-face classification and the Go-NoGo task show clear and specific effects of the food-type related PHSs. The food-face classification task can be considered as implicit with respect to the calorie dimension as it was task-irrelevant. By implementing PHS, suggesting desiring low-calorie food, an increase in implicit preference for low-calorie items and hence, reduction of an advantage for high-calorie-food at the early visual processing level was observed, followed by increased motivated attention and enhanced effective processing of images containing low-calorie items. The Go-NoGo task that required the explicit consideration of the calorie dimension indicated that PHS increased the pleasantness of low-calorie items and rendered high-calorie food less desirable; therefore, Go and NoGo stimuli may have both become emotionally arousing. Hence, deployment of excessive proactive control may have been necessary to inhibit task-irrelevant food-related emotions, decreasing the NoGo-N2 and inflating early Go- and NoGo-P3s. In addition, increased proactive control may have enhanced classification of salad-inappropriate, high-calorie food items and increased late Go-P3, possibly indicating enhanced response monitoring. Together these findings indicate that PHS is suitable to modulate food-preferences at several levels of processing. Therefore, PHS could fruitfully be employed in both studying and modulating the cognitive and affective subprocesses related to food preferences. The present results indicate that suitable PHS may support individuals in adjusting their food preferences if they desire to do so.

Ethical statement

The study had been approved by the ethics committee of the Institut für Psychologie of the Humboldt-Universität zu Berlin. Prior to the experiment, signed consent had been obtained. Participation was compensated either with 8 € per hour or course credits.

Acknowledgment

This research was supported by a scholarship to A.Z. by the Deutscher Akademischer Austauschdienst (DAAD). We thank Daniela Edreva and Lukas Wiegmann for help in data acquisition and Ulrike Bunzenthal, Rainer Kniesche, and Thomas Pinkpank for technical support.

The tasks and data of the current study is available in the following repository:

https://doi.org/10.17605/OSF.IO/SWP2A.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appet.2020.104713.

References

Albert, J., Lopez-Martin, S., & Carretie, L. (2010). Emotional context modulates response inhibition: Neural and behavioral data. *NeuroImage, 49*(1), 914–921. https://doi.org/10.1016/j.neuroimage.2009.08.045.

Allen, J. J., Iacono, W. G., Laravuso, J. J., & Dunn, L. A. (1995). An event-related potential investigation of posthypnotic recognition amnesia. *Journal of Abnormal Psychology, 104*(3), 421–430. https://doi.org/10.1037//0021-843x.104.3.421.

Augustinova, M., & Ferrand, L. (2012). Suggestion does not de-automatize word reading: Evidence from the semantically based stroop task. *Psychonomic Bulletin & Review, 19*(3), 521–527. https://doi.org/10.3758/s13423-012-0217-y.

Bartholdy, S., Rennalls, S. J., Jacques, C., Danby, H., Campbell, I. C., Schmidt, U., et al. (2017). Proactive and reactive inhibitory control in eating disorders. *Psychiatry Research, 255*, 432–440. https://doi.org/10.1016/j.psychres.2017.06.073.

Becker, C. A., Flaisch, T., Renner, B., & Schupp, H. T. (2016). Neural correlates of the perception of spoiled food stimuli. *Frontiers in Human Neuroscience, 10*, 302. https://doi.org/10.3389/fnhum.2016.00302.

Blechert, J., Meule, A., Busch, N. A., & Ohla, K. (2014). Food-pics: A database of free images of food for experimental research. https://sites.google.com/site/eatingandanxietylab/resources/food-pics.

Bongartz, W. (1985). German norms for the harvard group scale of hypnotic susceptibility, form A. *International Journal of Clinical and Experimental Hypnosis, 33*(2), 131–139. https://doi.org/10.1080/00207148508406643.

Braver, T. S. (2012). The variable nature of cognitive control: A dual mechanisms framework. *Trends in Cognitive Sciences, 16*(2), 106–113. https://doi.org/10.1016/j.tics.2011.12.010.

Carbine, K. A., Christensen, E., LeCheminant, J. D., Bailey, B. W., Tucker, L. A., & Larson, M. J. (2017). Testing food-related inhibitory control to high- and low-calorie food stimuli: Electrophysiological responses to high-calorie food stimuli predict calorie and carbohydrate intake. *Psychophysiology, 54*(7), 982–997. https://doi.org/10.1111/psyp.12860.

Clark, M. A., Springmann, M., Hill, J., & Tilman, D. (2019). Multiple health and environmental impacts of foods. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.1906908116.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences {Ind cd.* Hillsdale. NJ: Erihaum.

Cohen, J. (2016). Statistical power analysis. *Current Directions in Psychological Science, 1*(3), 98–101. https://doi.org/10.1111/1467-8721.ep10768783.

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods, 134*(1), 9–21.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750.

Dohle, S., Diel, K., & Hofmann, W. (2018). Executive functions and the self-regulation of eating behavior: A review. *Appetite, 124*, 4–9. https://doi.org/10.1016/j.appet.2017.05.041.

Donohue, S. E., Woldorff, M. G., Hopf, J. M., Harris, J. A., Heinze, H. J., & Schoenfeld, M. A. (2016). An electrophysiological dissociation of craving and stimulus-dependent attentional capture in smokers. *Cognitive, Affective, & Behavioral Neuroscience, 16*(6), 1114–1126. https://doi.org/10.3758/s13415-016-0457-9.

Duncker, K. (1938). Experimental modification of children's food preferences through social suggestion. *Journal of Abnormal and Social Psychology, 33*(4), 489.

Ebbeling, C. B., Sinclair, K. B., Pereira, M. A., Garcia-Lago, E., Feldman, H. A., & Ludwig, D. S. (2004). Compensation for energy intake from fast food among overweight and lean adolescents. *Journal of the American Medical Association, 291*(23), 2828–2833.

Emond, J. A., Longacre, M. R., Drake, K. M., Titus, L. J., Hendricks, K., MacKenzie, T., ... Dalton, M. A. (2019). Influence of child-targeted fast food TV advertising exposure on fast food intake: A longitudinal study of preschool-age children. *Appetite, 140*, 134–141. https://doi.org/10.1016/j.appet.2019.05.012.

Enriquez-Geppert, S., Konrad, C., Pantev, C., & Huster, R. J. (2010). Conflict and inhibition differentially affect the N200/P300 complex in a combined go/nogo and stop-signal task. *NeuroImage, 51*(2), 877–887. https://doi.org/10.1016/j.neuroimage.2010.02.043.

Folstein, J. R., & Van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: A review. *Psychophysiology, 45*(1), 152–170. https://doi.org/10.1111/j.1469-8986.2007.00602.x.

Forouzanfar, M. H., Alexander, L., Anderson, H. R., Bachman, V. F., Biryukov, S., Brauer, M., ... Murray, C. J. (2015). Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990–2013: A systematic analysis for the global burden of disease study 2013. *The Lancet, 386*(10010), 2287–2323. https://doi.org/10.1016/s0140-6736(15)00128-2.

Frank, S., Laharnar, N., Kullmann, S., Veit, R., Canova, C., Hegner, Y. L., ... Preissl, H. (2010). Processing of food pictures: Influence of hunger, gender and calorie content. *Brain Research, 1350*, 159–166. https://doi.org/10.1016/j.brainres.2010.04.030.

Fromer, R., Sturmer, B., & Sommer, W. (2016). The better, the bigger: The effect of graded positive performance feedback on the reward positivity. *Biological Psychology, 114*, 61–68. https://doi.org/10.1016/j.biopsycho.2015.12.011.

Gajewski, P. D., & Falkenstein, M. (2013). Effects of task complexity on ERP components in Go/Nogo tasks. *International Journal of Psychophysiology, 87*(3), 273–278. https://doi.org/10.1016/j.ijpsycho.2012.08.007.

Green, J. P., Barabasz, A. F., Barrett, D., & Montgomery, G. H. (2005). Forging ahead: The 2003 APA division 30 definition of hypnosis. *International Journal of Clinical and Experimental Hypnosis, 53*(3), 259–264. https://doi.org/10.1080/00207140590961321.

Guerrieri, R., Nederkoorn, C., & Jansen, A. (2008). The interaction between impulsivity and a varied food environment: Its influence on food intake and overweight. *International Journal of Obesity, 32*(4), 708–714. https://doi.org/10.1038/sj.ijo.0803770 2005.

Haddad, L., Hawkes, C., Waage, J., Webb, P., Godfray, C., & Toulmin, C. (2016). *Food systems and diets: Facing the challenges of the 21st century*.

Hammond, D. C. (1990). *Handbook of hypnotic suggestions and metaphors.* WW Norton & Company.

Hammond, D. C. (1998). *Hypnotic induction and suggestion.* Chicago, IL: American Society of Clinical Hypnosis.

Hertel, P. T., & Mathews, A. (2011). Cognitive bias modification: Past perspectives, current findings, and future applications. *Perspectives on Psychological Science, 6*(6), 521–536. https://doi.org/10.1177/1745691611421205.

Hickey, C., Chelazzi, L., & Theeuwes, J. (2010). Reward changes salience in human vision via the anterior cingulate. *Journal of Neuroscience, 30*(33), 11096–11103. https://doi.org/10.1523/jneurosci.1026-10.2010.

Iani, C., Ricci, F., Baroni, G., & Rubichi, S. (2009). Attention control and susceptibility to hypnosis. *Consciousness and Cognition, 18*(4), 856–863. https://doi.org/10.1016/j.concog.2009.07.002.

Iani, C., Ricci, F., Gherri, E., & Rubichi, S. (2006). Hypnotic suggestion modulates cognitive conflict: The case of the flanker compatibility effect. *Psychological Science, 17*(8), 721–727. https://doi.org/10.1111/j.1467-9280.2006.01772.x.

Jensen, M. P., Jamieson, G. A., Lutz, A., Mazzoni, G., McGeown, W. J., Santarcangelo, E. L., ... Terhune, D. B. (2017). New directions in hypnosis research: Strategies for advancing the cognitive and clinical neuroscience of hypnosis. *Neurosci Conscious, 3*(1), https://doi.org/10.1093/nc/nix004.

Kihlstrom, J. F. (2014). Hypnosis and cognition. *Psychology of Consciousness: Theory, Research, and Practice, 1*(2), 139–152. https://doi.org/10.1037/cns0000014.

Killgore, W. D. S., Young, A. D., Femia, L. A., Bogorodzki, P., Rogowska, J., & Yurgelun-Todd, D. A. (2003). Cortical and limbic activation during viewing of high- versus low-calorie foods. *NeuroImage, 19*(4), 1381–1394. https://doi.org/10.1016/s1053-8119(03)00191-5.

Kirsch, I., Montgomery, G., & Sapirstein, G. (1995). Hypnosis as an adjunct to cognitive-behavioral psychotherapy- A meta-analysis. *Journal of Consulting and Clinical Psychology, 63*(2), 214.

Klein, K. B., & Spiegel, D. (1989). Modulation of gastric acid secretion by hypnosis. *Gastroenterology, 96*(6), 1383–1387.

Kreidler, S. M., Muller, K. E., Grunwald, G. K., Ringham, B. M., Coker-Dukowitz, Z. T., Sakhadeo, U. R., ... Glueck, D. H. (2013). GLIMMPSE: Online power computation for linear models with and without a baseline covariate. *Journal of Statistical Software, 54*(10), https://doi.org/10.18637/jss.v054.i10.

Liu, T., Xiao, T., & Shi, J. (2017). Neural correlates of response inhibition and conflict control on facial expressions. *Frontiers in Human Neuroscience, 11*, 657. https://doi.org/10.3389/fnhum.2017.00657.

London, P. (1961). Subject characteristics in hypnosis research. I. A survey of experience, interest, and opinion. *International Journal of Clinical and Experimental Hypnosis, 9*, 151–161. https://doi.org/10.1080/00207146108409670.

London, P., Cooper, L. M., & Johnson, H. J. (1962). Subject characteristics in hypnosis research: II. Attitudes towards hypnosis, volunteer status, and personality measures. III. Some correlates of hypnotic susceptibility. *International Journal of Clinical and Experimental Hypnosis, 10*, 13–21. https://doi.org/10.1080/00207146208415861.

Lowe, C. J., Hall, P. A., & Staines, W. R. (2014). The effects of continuous theta burst stimulation to the left dorsolateral prefrontal cortex on executive function, food cravings, and snack food consumption. *Psychosomatic Medicine, 76*(7), 503–511. https://doi.org/10.1097/PSY.0000000000000090.

Ludwig, V. U., Stelzel, C., Krutiak, H., Magrabi, A., Steimke, R., Paschke, L. M., ... Walter, H. (2014). The suggestible brain: Posthypnotic effects on value-based decision-making. *Social Cognitive and Affective Neuroscience, 9*(9), 1281–1288. https://doi.org/10.1093/scan/nst110.

Lynn, S. J., Green, J. P., Polizzi, C. P., Ellenberg, S., Gautam, A., & Aksen, D. (2019). Hypnosis, hypnotic phenomena, and hypnotic responsiveness: Clinical and research foundations-A 40-year perspective. *International Journal of Clinical and Experimental Hypnosis, 67*(4), 475–511. https://doi.org/10.1080/00207144.2019.1649541.

Maier-Noth, A. (2019). Early development of food preferences and healthy eating habits in infants and young children. *Nestle Nutrition Institute Workshop Series, 91*, 11–20. https://doi.org/10.1159/000493674.

Meule, A., Kubler, A., & Blechert, J. (2013). Time course of electrocortical food-cue responses during cognitive regulation of craving. *Frontiers in Psychology, 4*, 669. https://doi.org/10.3389/fpsyg.2013.00669.

Milburn, M. C. (2010). Cognitive-behavior therapy and change: Unconditional self acceptance and hypnosis in CBT. *Journal of Rational-Emotive and Cognitive-Behavior Therapy, 29*(3), 177–191. https://doi.org/10.1007/s10942-010-0121-1.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to

complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734.
Nederkoorn, C., Guerrieri, R., Havermans, R. C., Roefs, A., & Jansen, A. (2009). The interactive effect of hunger and impulsivity on food intake and purchase in a virtual supermarket. *International Journal of Obesity, 33*(8), 905–912. https://doi.org/10.1038/ijo.2009.98 2005.
Nederkoorn, C., Houben, K., Hofmann, W., Roefs, A., & Jansen, A. (2010). Control yourself or just eat what you like? Weight gain over a year is predicted by an interactive effect of response inhibition and implicit preference for snack foods. *Health Psychology, 29*(4), 389–393. https://doi.org/10.1037/a0019921.
Nijs, I. M., Franken, I. H., & Muris, P. (2008). Food cue-elicited brain potentials in obese and healthy-weight individuals. *Eating Behaviors, 9*(4), 462–470. https://doi.org/10.1016/j.eatbeh.2008.07.009.
Nijs, I. M., Muris, P., Euser, A. S., & Franken, I. H. (2010). Differences in attention to food and food intake between overweight/obese and normal-weight females under conditions of hunger and satiety. *Appetite, 54*(2), 243–254. https://doi.org/10.1016/j.appet.2009.11.004.
OECD. (2017). *Obesity update.* last accessed April 15, 2018. Retrieved from http://www.oecd.org/health/obesity-update.htm.
Ouyang, G., Schacht, A., Zhou, C., & Sommer, W. (2013). Overcoming limitations of the ERP method with residue iteration decomposition (RIDE): A demonstration in go/no-go experiments. *Psychophysiology, 50*(3), 253–265. https://doi.org/10.1111/psyp.12004.
Ouyang, G., Sommer, W., & Zhou, C. (2015). Updating and validating a new framework for restoring and analyzing latency-variable ERP components from single trials with residue iteration decomposition (RIDE). *Psychophysiology, 52*(6), 839–856. https://doi.org/10.1111/psyp.12411.
Perri, R. L., Rossani, F., & Di Russo, F. (2019). Neuroelectric evidences of top-down hypnotic modulation associated with somatosensory processing of sensory and limbic regions. *NeuroImage, 202*, 116104. https://doi.org/10.1016/j.neuroimage.2019.116104.
Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology, 118*(10), 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019.
Pool, E., Brosch, T., Delplanque, S., & Sander, D. (2016). Attentional bias for positive emotional stimuli: A meta-analytic investigation. *Psychological Bulletin, 142*(1), 79–106. https://doi.org/10.1037/bul0000026.
Prickett, C., Brennan, L., & Stolwyk, R. (2015). Examining the relationship between obesity and cognitive function: A systematic literature review. *Obesity Research & Clinical Practice, 9*(2), 93–113. https://doi.org/10.1016/j.orcp.2014.05.001.
Raz, A., Fan, J., & Posner, M. I. (2005). Hypnotic suggestion reduces conflict in the human brain. *Proceedings of the National Academy of Sciences of the United States of America, 102*(28), 9978–9983. https://doi.org/10.1073/pnas.0503064102.
Raz, A., Landzberg, K. S., Schweizer, H. R., Zephrani, Z. R., Shapiro, T., Fan, J., et al. (2003). Posthypnotic suggestion and the modulation of Stroop interference under cycloplegia. *Consciousness and Cognition, 12*(3), 332–346. https://doi.org/10.1016/s1053-8100(03)00024-2.
Rebetez, M. M., Rochat, L., Billieux, J., Gay, P., & Van der Linden, M. (2015). Do emotional stimuli interfere with two distinct components of inhibition? *Cognition & Emotion, 29*(3), 559–567. https://doi.org/10.1080/02699931.2014.922054.
Roberts, R. J., Jr., & Pennington, B. F. (1996). An interactive framework for examining prefrontal cognitive processes. *Developmental Neuropsychology, 12*(1), 105–126.
Rodgers, A., Woodward, A., Swinburn, B., & Dietz, W. H. (2018). Prevalence trends tell us what did not precipitate the US obesity epidemic. *The Lancet Public Health, 3*(4), e162–e163. https://doi.org/10.1016/s2468-2667(18)30021-5.
Sarlo, M., Ubel, S., Leutgeb, V., & Schienle, A. (2013). Cognitive reappraisal fails when attempting to reduce the appetitive value of food: An ERP study. *Biological Psychology, 94*(3), 507–512. https://doi.org/10.1016/j.biopsycho.2013.09.006.
Schacht, A., Adler, N., Chen, P., Guo, T., & Sommer, W. (2012). Association with positive outcome induces early effects in event-related brain potentials. *Biological Psychology, 89*(1), 130–136. https://doi.org/10.1016/j.biopsycho.2011.10.001.
Schmidt, B., Hecht, H., Naumann, E., & Miltner, W. H. R. (2017). The Power of mind: Blocking visual perception by hypnosis. *Scientific Reports, 7*(1), 4889. https://doi.org/10.1038/s41598-017-05195-2.
Schrauwen, P., & Westerterp, K. R. (2000). The role of high-fat diets and physical activity in the regulation of body weight. *British Journal of Nutrition, 84*(4), 417–427. https://doi.org/10.1017/s0007114500001720.
Schulz, K. P., Fan, J., Magidina, O., Marks, D. J., Hahn, B., & Halperin, J. M. (2007). Does the emotional go/no-go task really measure behavioral inhibition? Convergence with measures on a non-emotional analog. *Archives of Clinical Neuropsychology, 22*(2), 151–160. https://doi.org/10.1016/j.acn.2006.12.001.
Schupp, H. T., Flaisch, T., Stockburger, J., & Junghofer, M. (2006). Emotion and attention: Event-related brain potential studies. *Progress in Brain Research, 156*, 31–51. https://doi.org/10.1016/S0079-6123(06)56002-9.
Seidell, J. C. (1998). Dietary fat and obesity: An epidemiologic perspective. *American Journal of Clinical Nutrition, 67*(3), 546S–550S.
Sheehan, P. W., Donovan, P., & MacLeod, C. M. (1988). Strategy manipulation and the Stroop effect in hypnosis. *Journal of Abnormal Psychology, 97*(4), 455–460. https://doi.org/10.1037/0021-843x.97.4.455.
Shor, R. E., & Orne, E. C. (1962). *Harvard group scale of hypnotic susceptibility.* Consulting Psychologists Press.
Shor, R. E., & Orne, E. C. (1963). Norms on the Harvard group scale of hypnotic susceptibility, form A. *International Journal of Clinical and Experimental Hypnosis, 11*, 39–47. https://doi.org/10.1080/00207146308409226.
Smith, E., Hay, P., Campbell, L., & Trollor, J. N. (2011). A review of the association between obesity and cognitive function across the lifespan: Implications for novel approaches to prevention and treatment. *Obesity Reviews, 12*(9), 740–755. https://doi.org/10.1111/j.1467-789X.2011.00920.x.
Stockburger, J., Schmalzle, R., Flaisch, T., Bublatzky, F., & Schupp, H. T. (2009). The impact of hunger on food cue processing: An event-related brain potential study. *NeuroImage, 47*(4), 1819–1829. https://doi.org/10.1016/j.neuroimage.2009.04.071.
Stockburger, J., Weike, A. I., Hamm, A. O., & Schupp, H. T. (2008). Deprivation selectively modulates brain potentials to food pictures. *Behavioral Neuroscience, 122*(4), 936–942. https://doi.org/10.1037/a0012517.
Stok, F. M., Hoffmann, S., Volkert, D., Boeing, H., Ensenauer, R., Stelmach-Mardas, M., ... Renner, B. (2017). The DONE framework: Creation, evaluation, and updating of an interdisciplinary, dynamic framework 2.0 of determinants of nutrition and eating. *PloS One, 12*(2), e0171077. https://doi.org/10.1371/journal.pone.0171077.
Tee, J. Y. H., Gan, W. Y., Tan, K. A., & Chin, Y. S. (2018). Obesity and unhealthy lifestyle associated with poor executive function among Malaysian adolescents. *PloS One, 13*(4), e0195934. https://doi.org/10.1371/journal.pone.0195934.
Terhune, D. B., Cardena, E., & Lindgren, M. (2010). Disruption of synaesthesia by posthypnotic suggestion: An ERP study. *Neuropsychologia, 48*(11), 3360–3364. https://doi.org/10.1016/j.neuropsychologia.2010.07.004.
Toepel, U., Knebel, J. F., Hudry, J., le Coutre, J., & Murray, M. M. (2009). The brain tracks the energetic value in food images. *NeuroImage, 44*(3), 967–974. https://doi.org/10.1016/j.neuroimage.2008.10.005.
Verbruggen, F., & De Houwer, J. (2007). Do emotional stimuli interfere with response inhibition? Evidence from the stop signal paradigm. *Cognition & Emotion, 21*(2), 391–403. https://doi.org/10.1080/02699930600625081.
Watson, T. D., & Garvey, K. T. (2013). Neurocognitive correlates of processing food-related stimuli in a Go/No-go paradigm. *Appetite, 71*, 40–47. https://doi.org/10.1016/j.appet.2013.07.007.
Weisbrod, M., Kiefer, M., Marzinzik, F., & Spitzer, M. (2000). Executive control is disturbed in schizophrenia: Evidence from event-related potentials in a go/NoGo task. *Biological Psychiatry, 47*(1), 51–60.
Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., ... Murray, C. J. L. (2019). Food in the anthropocene: The EAT–lancet commission on healthy diets from sustainable food systems. *The Lancet, 393*(10170), 447–492. https://doi.org/10.1016/s0140-6736(18)31788-4.
Wilson, B. (2015). *First bite: How we learn to eat.* Basic Books.
Yang, S., Luo, W., Zhu, X., Broster, L. S., Chen, T., Li, J., et al. (2014). Emotional content modulates response inhibition and perceptual processing. *Psychophysiology, 51*(11), 1139–1146. https://doi.org/10.1111/psyp.12255.
Yang, Y., Shields, G. S., Guo, C., & Liu, Y. (2018). Executive function performance in obesity and overweight individuals: A meta-analysis and review. *Neuroscience & Biobehavioral Reviews, 84*, 225–244. https://doi.org/10.1016/j.neubiorev.2017.11.020.
Zahedi, A., Stuermer, B., Abdel Rahman, R., & Sommer, W. (2019). Common and specific loci of Stroop effects in vocal and manual tasks, revealed by event-related brain potentials and posthypnotic suggestions. *Journal of Experimental Psychology: General, 148*(9), 1575.
Zahedi, A., Stuermer, B., Hatami, J., Rostami, R., & Sommer, W. (2017). Eliminating stroop effects with post-hypnotic instructions: Brain mechanisms inferred from EEG. *Neuropsychologia*. https://doi.org/10.1016/j.neuropsychologia.2017.01.006.
Zhao, D., Lin, H., Xie, S., & Liu, Z. (2019). Emotional arousal elicited by irrelevant stimuli affects event-related potentials (ERPs) during response inhibition. *Physiology & Behavior, 206*, 134–142. https://doi.org/10.1016/j.physbeh.2019.04.005.